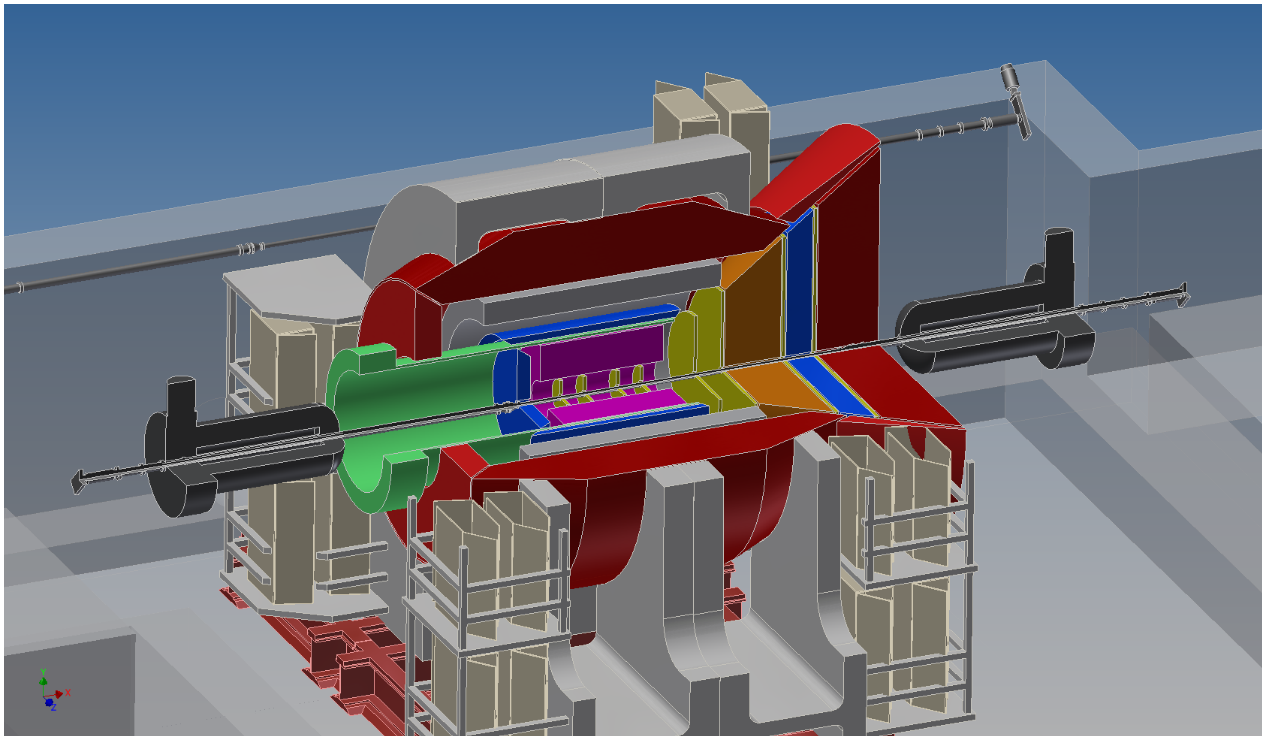
ePHENIX



A.Bazilevsky

for ePHENIX LoI Writing Committee

BNL ALD charge for Letter of Intent

- Charge from BNL ALD to PHENIX and STAR to:
  - "Provide specific plans to upgrade/reconfigure the detectors from their present form to first-generation eRHIC detectors"
  - Describe "the physics reach of the upgraded detector"
    - Based on detector capabilities
    - Considering key measurements as described in EIC White Paper (arXiv: 1212.1701)
- ePHENIX LOI Writing Committee formed in May
  - Sasha Bazilevsky (co-chair), Kieran Boyle (co-chair), Abhay Deshpande, Jin Huang, Tom Hemmick, Itaru Nakagawa, Craig Woody, John Haggerty, Dave Morrison, Jamie Nagle
- Submitted to ALD on August 30.

ePHENIX LoI Path

Evolve sPHENIX (pp and HI detector) to ePHENIX (DIS detector)

- ✓ sPHENIX MIE: Make sure sPHENIX upgrade is consistent with ePHENIX plans

Gratefully use the experience and developments by BNL EIC group

- ✓ https://wiki.bnl.gov/eic/index.php/Detector_Design_Requirements
- ✓ Maintained generators at racf (e.g. PYTHIA, MILOU, RAPGAP)

Key physics measurements as outlined in EIC White Paper: arXiv:12.12.1701

- ✓ Reproduce some of projection plots for ePHENIX expected acceptances/efficiencies
- ✓ Include 10 GeV electron beams (White Paper used only 5 GeV for stage 1)
- ✓ Make projections for 10 fb^{-1} for each energy/species (as in White Paper)
  1 fb^{-1}/month expected for 10^{33} cm^{-2} s^{-1} ep luminosity

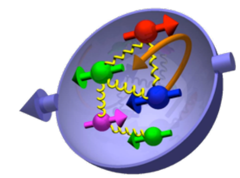
Develop detector requirements to accomplish physics goals

- ✓ Balance between cost and capabilities

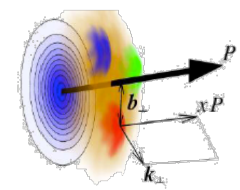
Discuss among the BNL EIC community to get criticism/comments/suggestions

EIC Physics

Distribution of quarks and gluons and their spins in space and momentum inside the nucleon

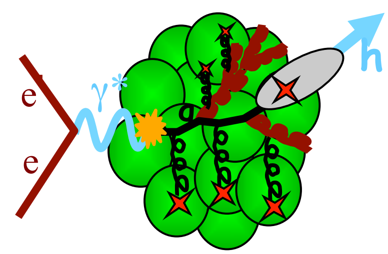


- Nucleon helicity structure
- Parton transverse motion in the nucleon
- Spacial distribution of partons and parton orbital angular momentum



QCD in nuclei

- Nuclear modification of parton distributions
- Gluon saturation
- Propagation/Hadronization in nuclear matter



~~Weak interactions & beyond standard model~~

- Require highest energy and lum. -> not for stage-1

General Detector Concept

Inclusive DIS and scattered electron measurements

With focus in e-going direction and barrel

High resolution EMCal and tracking; minimal material budget

Semi-inclusive DIS and hadron ID

With focus in h-going direction and barrel

Barrel: DIRC for p_h<4 GeV/c

h-going direction: aerogel for lower p_h and gas RICH for higher p_h

Exclusive DIS (DVCS etc.)

EMCal and tracking coverage in $-4<\eta<4$

High granularity EMCal in e-going direction

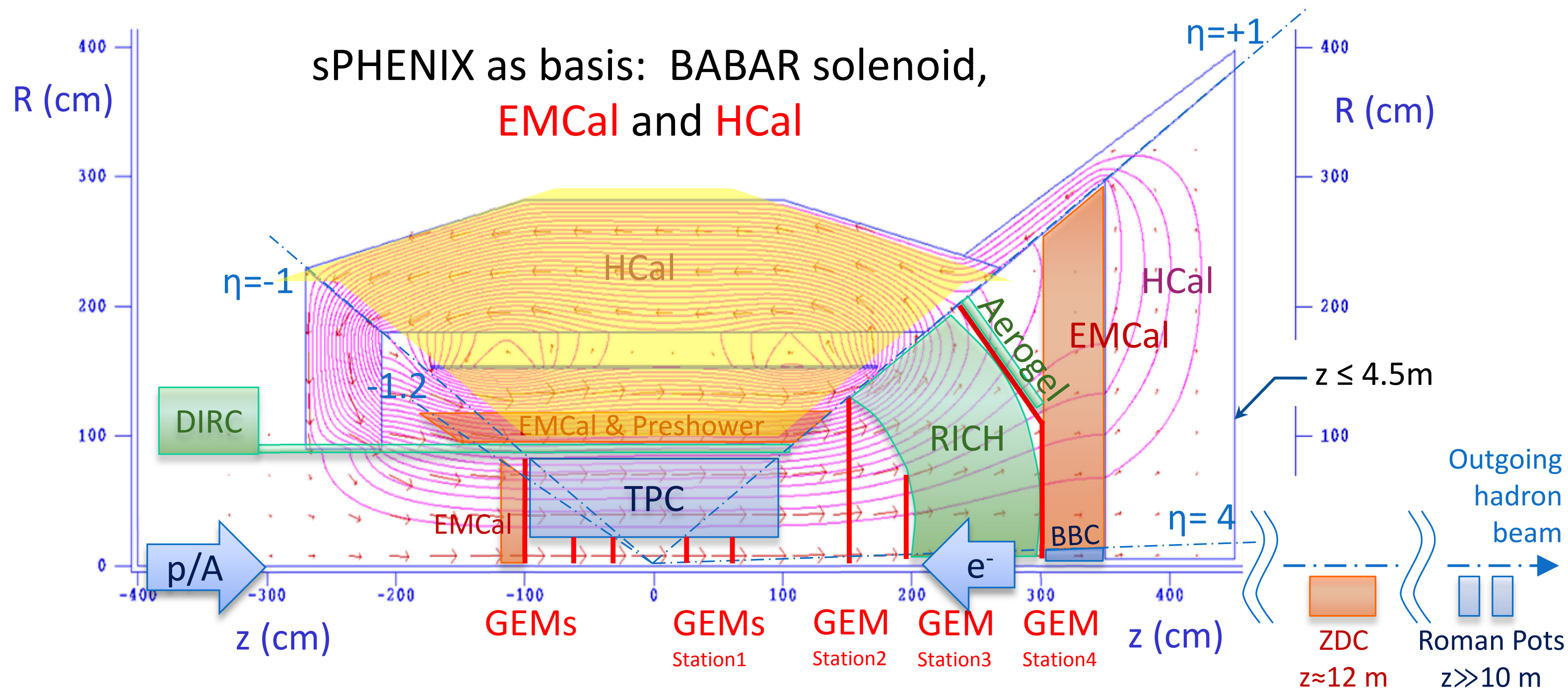
Roman Pots in h-going direction

Diffractive

Rapidity gap measurements: HCal in $-1<\eta<5$; EMCal in $-4<\eta<4$

ZDC in h-going direction

ePHENIX Detector Concept



- -4<η<-1 (e-going):
  - Crystal calorimeter with high energy and position resolution
  - GEM Trackers
- -1<η<1 (barrel):
  - Add Compact-TPC and DIRC

- 1<η<4 (h-going):
  - HCal & EMCal (1<η<5)
  - GEM Trackers
  - Aerogel RICH (1<η<2)
  - Gas RICH
- Far Forward (h-going)
  - ZDC and Roman Pots

BaBar Magnet


BaBar solenoid in its transfer frame, May 17 2013

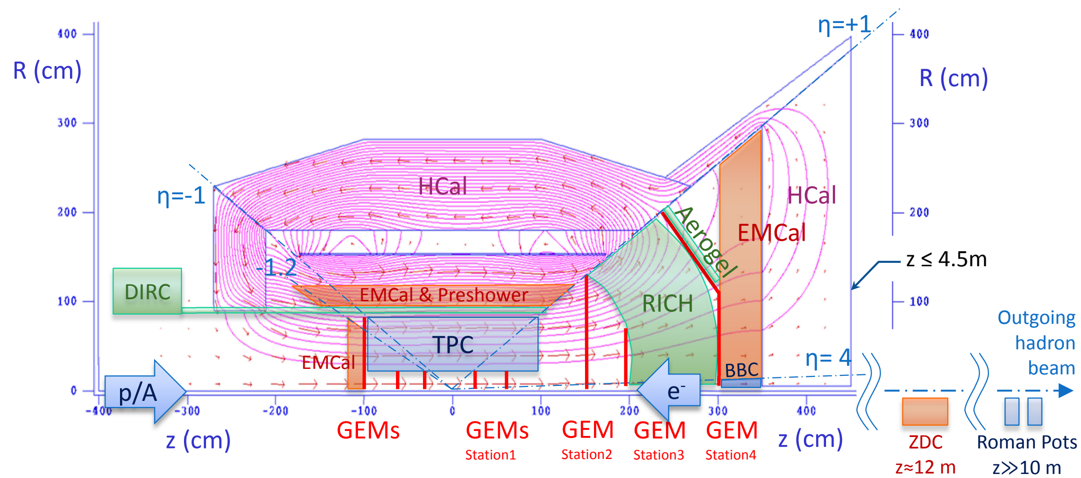
Major Parameters:

- ✓ Superconducting Solenoid
- ✓ Field: 1.5T
- ✓ Inner radius: 140 cm
- ✓ Outer radius: 173 cm
- ✓ Length: 385 cm

Higher current density at magnet ends and field shaping in forward angles provide high analyzing power for momentum determination in e-going and h-going directions

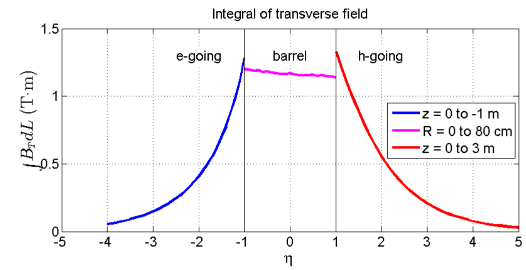
Flux return and field shaping:

Forward HCal
Steel lapmshade
Barrel HCal
Steel endcup

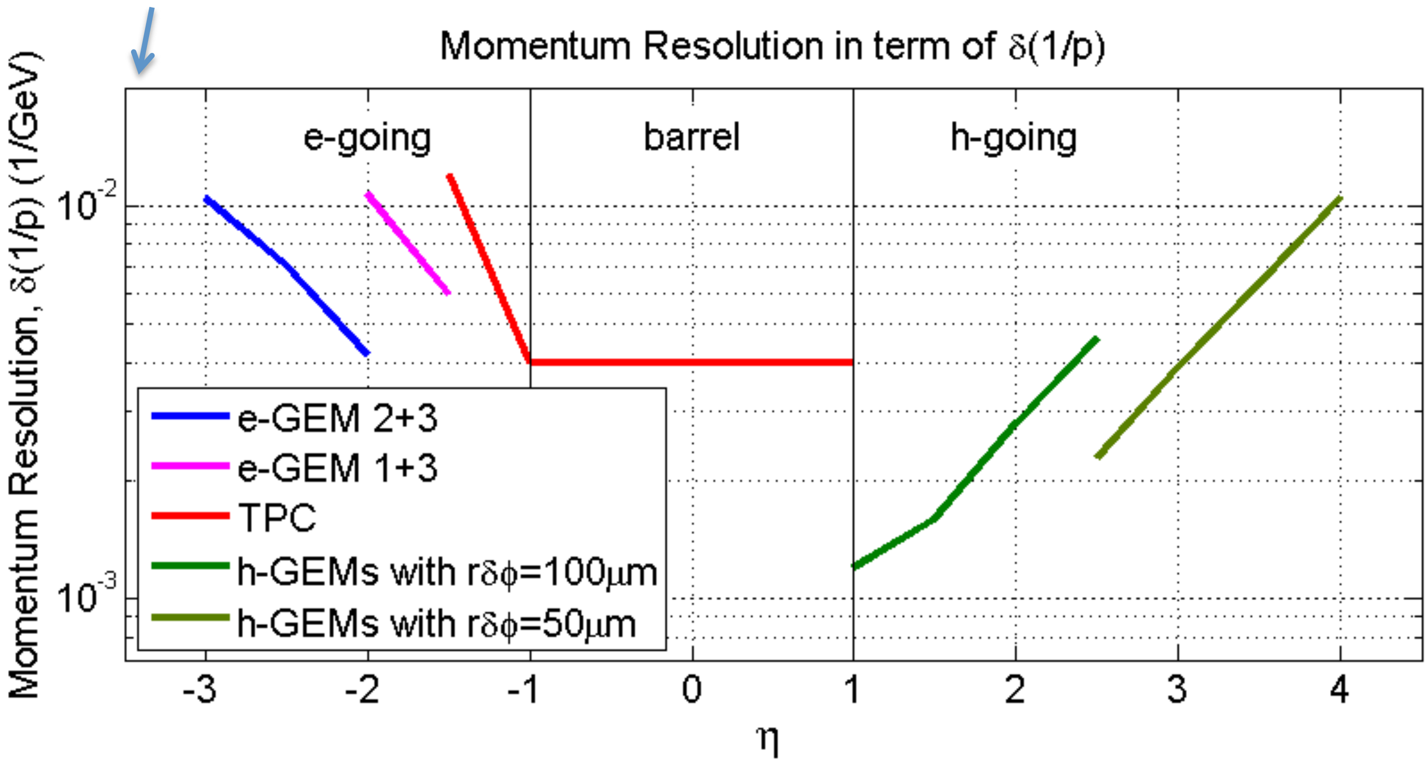


Main space limitation observed: |z|<4.5m
(due to focusing magnet location)

Momentum Resolution



$\delta p/p \sim a \times p$



Good resolution over full tracking acceptance ($-3<\eta<4$)

e-going, $\sigma_p/p \sim (0.4\text{-}1.0\%)\times p$: primarily needed for electron ID (E/p)

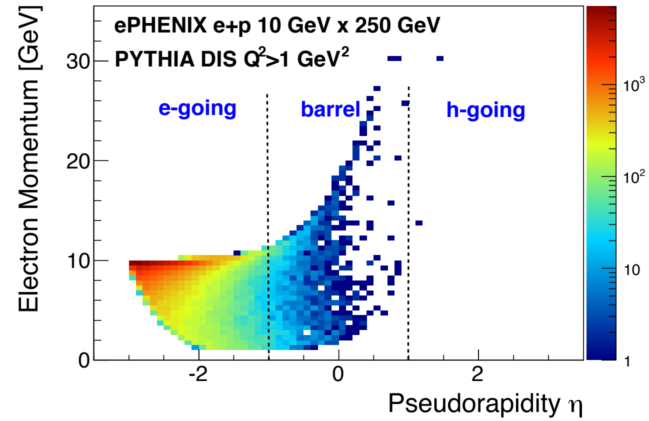
barrel, $\sigma_p/p \sim 0.4\%\times p$: hadron momentum, electron momentum at p<10 GeV/c

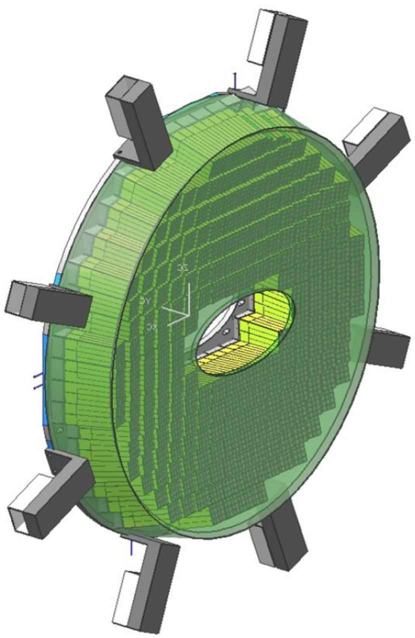
h-going, $\sigma_p/p \sim (0.1\text{-}1.0\%)\times p$: crucial for PID

DIS kinematics

Measure scattered electron energy and angle:

$$Q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right) \qquad y = 1 - \frac{E'}{E}\cos^2\left(\frac{\theta}{2}\right) \qquad x = \frac{Q^2}{sy}$$

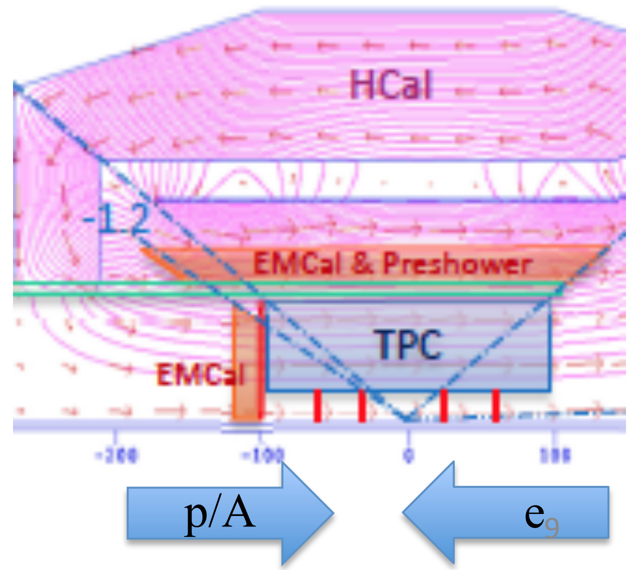




TDR for PANDA
arXiv:0810.1216

- Endcap Calorimeter:
  - $PbWO_4$ crystal
  - Similar to PANDA endcap design
  - $\sigma_E/E \sim 1.5\%/\sqrt{E}$
  - $\sigma_X < 3\text{mm}/\sqrt{E}$
- Barrel Calorimeter:
  - sPHENIX EMCal
  - Tungsten based
  - $\sigma_E/E \sim 12\%/\sqrt{E}$

Scattering mainly in e-going direction and barrel



Inclusive DIS and Kinematics

eID and background rejection

Hadron rejection:

EMCal energy response and E/p

×20-30 at 1 GeV/c

×100 at 3 GeV/c

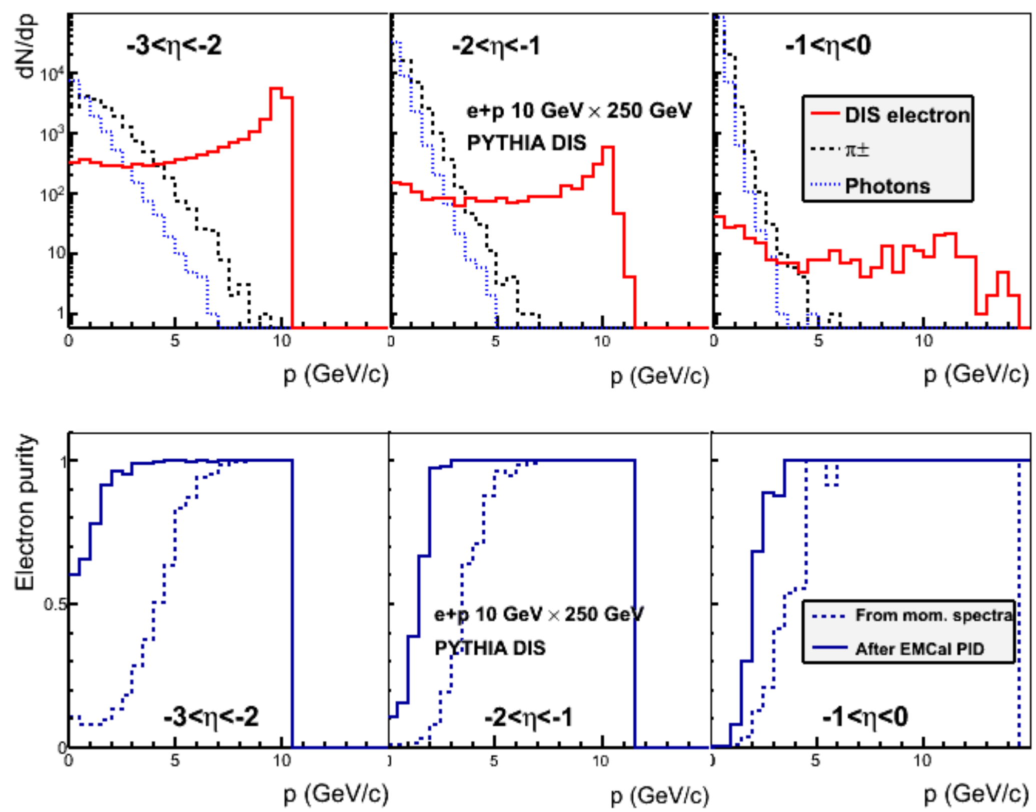
EMCal shower profile

Expect ×3-10

Not yet included in plots

EMCal long. segmentation and/or preshower

For future considerations



Photon rejection ($\gamma \rightarrow e^+e^-$)

Minimal material

Rejection with tracking and E/p

GEANT study is ongoing

Reliable eID down to

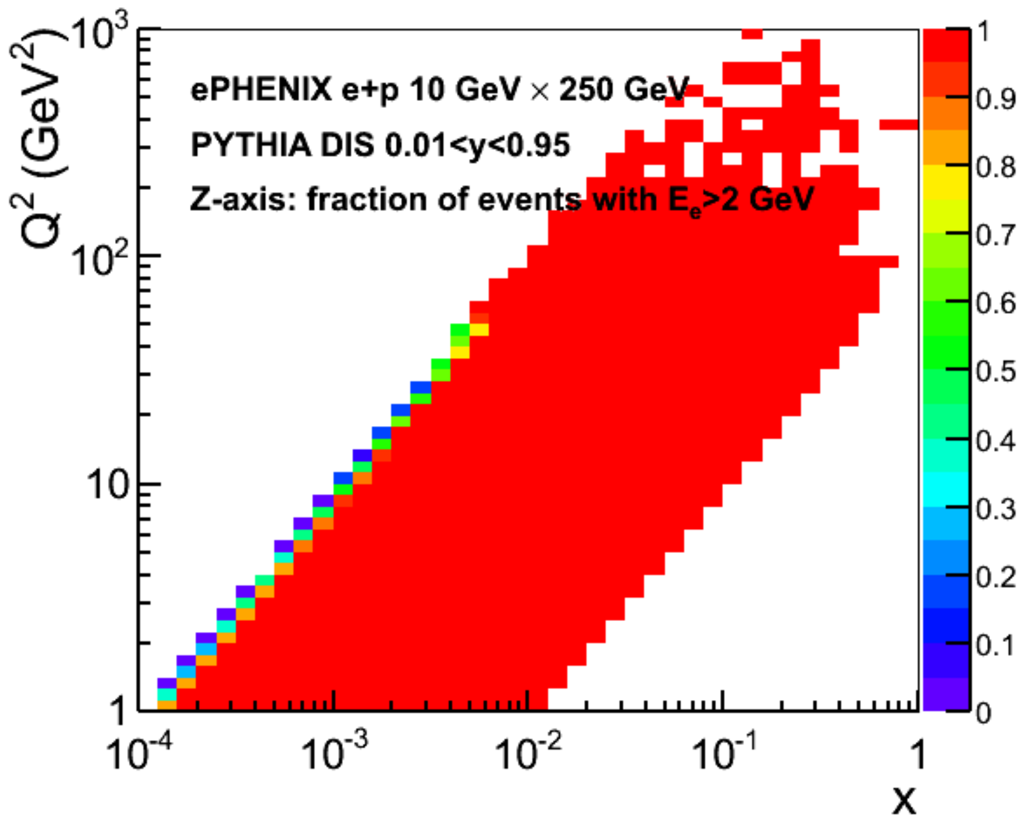
p=2 GeV/c for 10 GeV e-beam

p=1 GeV/c for 5 GeV e-beam

Inclusive DIS and Kinematics

What if poor eID at <2 GeV/c

Don't lose much of the (x,Q^2) space



Inclusive DIS and Kinematics

Resolutions for (x,Q^2)

For perfect angle measurements:

$$\frac{\sigma_{Q^2}}{Q^2} = \frac{\sigma_{E'}}{E'} \qquad \frac{\sigma_x}{x} = \frac{1}{y}\frac{\sigma_{E'}}{E'}$$

Defines the precision of unfolding technique to correct for smearing due to detector effects

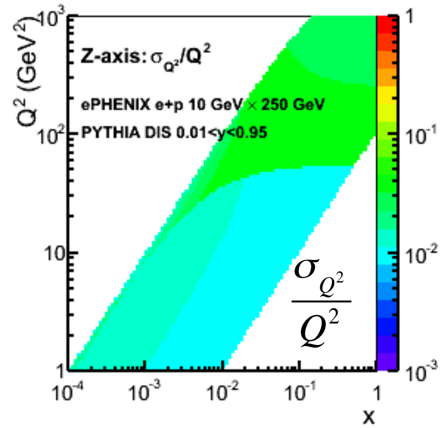
Results in statistics migration from bin to bin –> bin survival probability

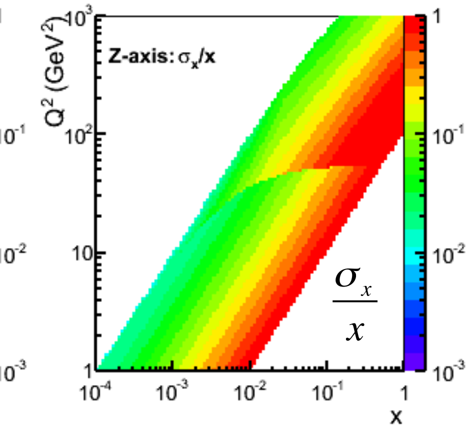
From HERMES experience: ~80% needed

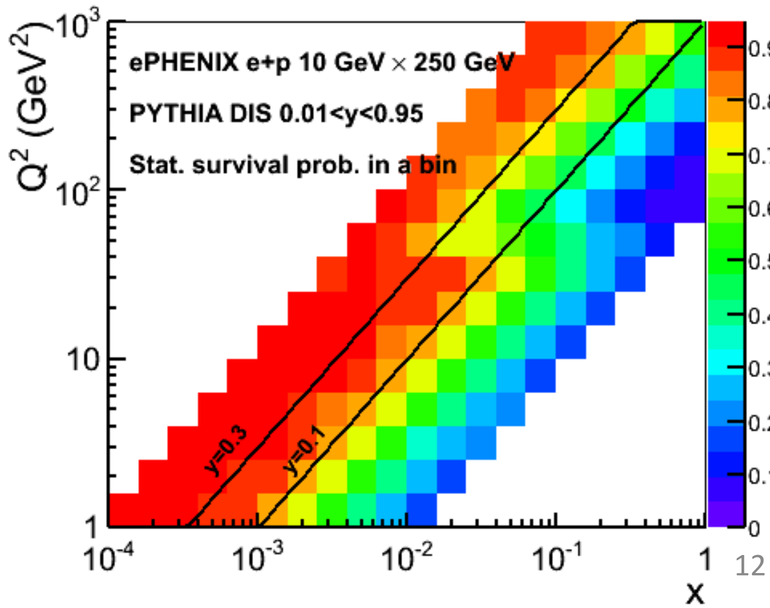
Enough precision for scattered angle from EMCal position resolution –> no effect on bin survivability

Jacqet-Blondel method (with hadronic final state) will help at lower y and higher Q^2

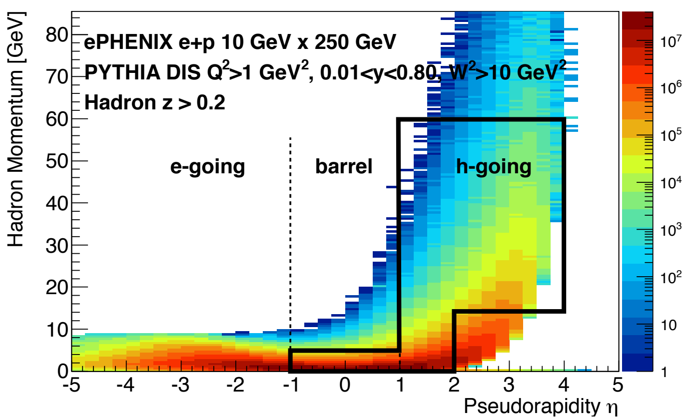
Plan to exercise with full unfolding to quantify the detector and radiation effects



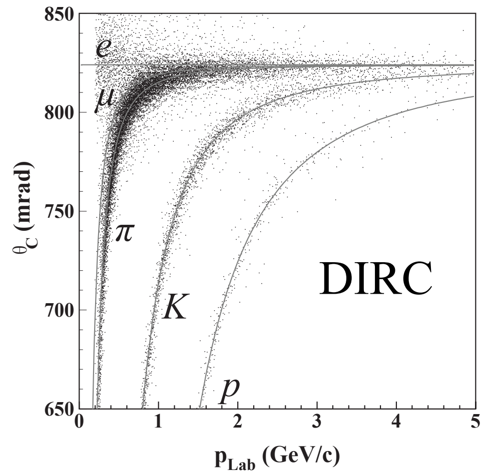


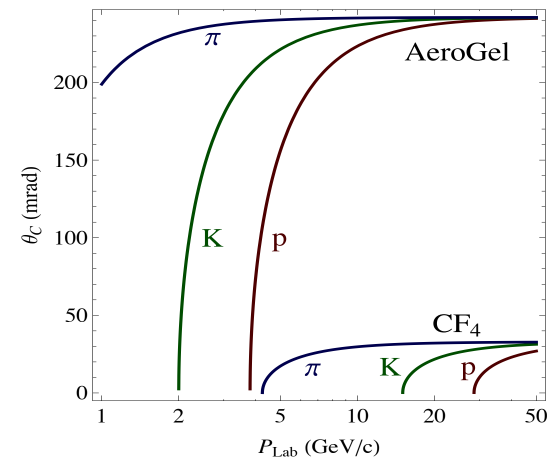


Semi-inclusive DIS and hadron ID



Focus on h-going direction and barrel





DIRC:

-1<η<1

PID at <4 GeV/c

Aerogel:

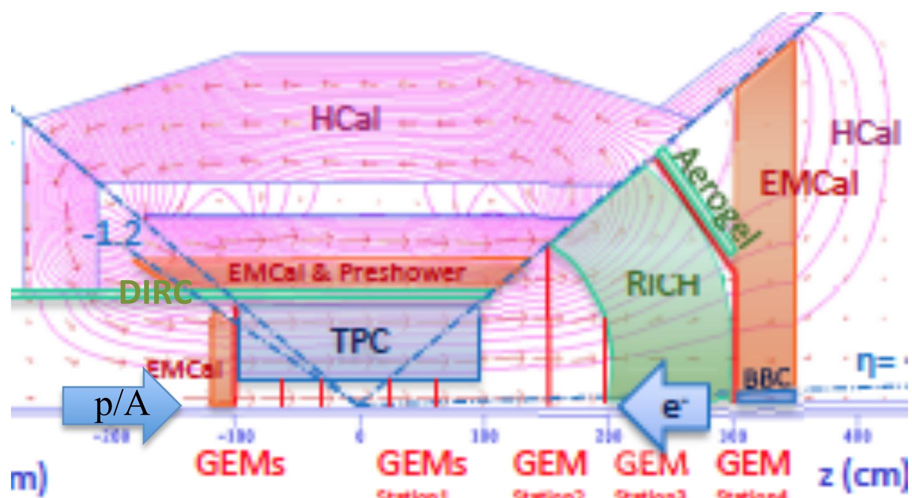
1<η<2

PID at <15 GeV/c

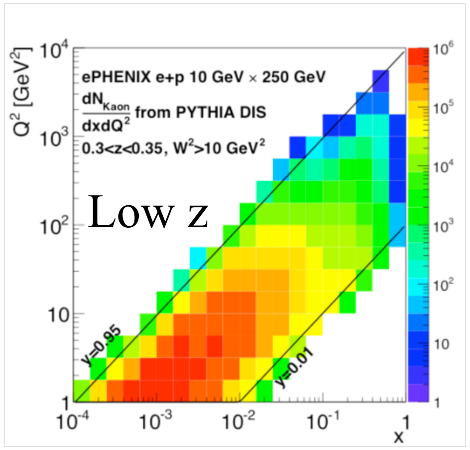
Gas RICH (CF4):

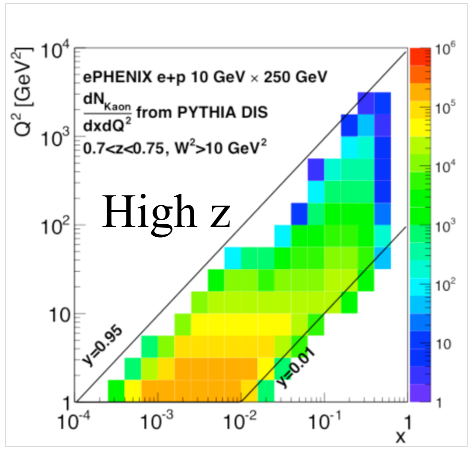
1<η<4

PID at <60 GeV/c



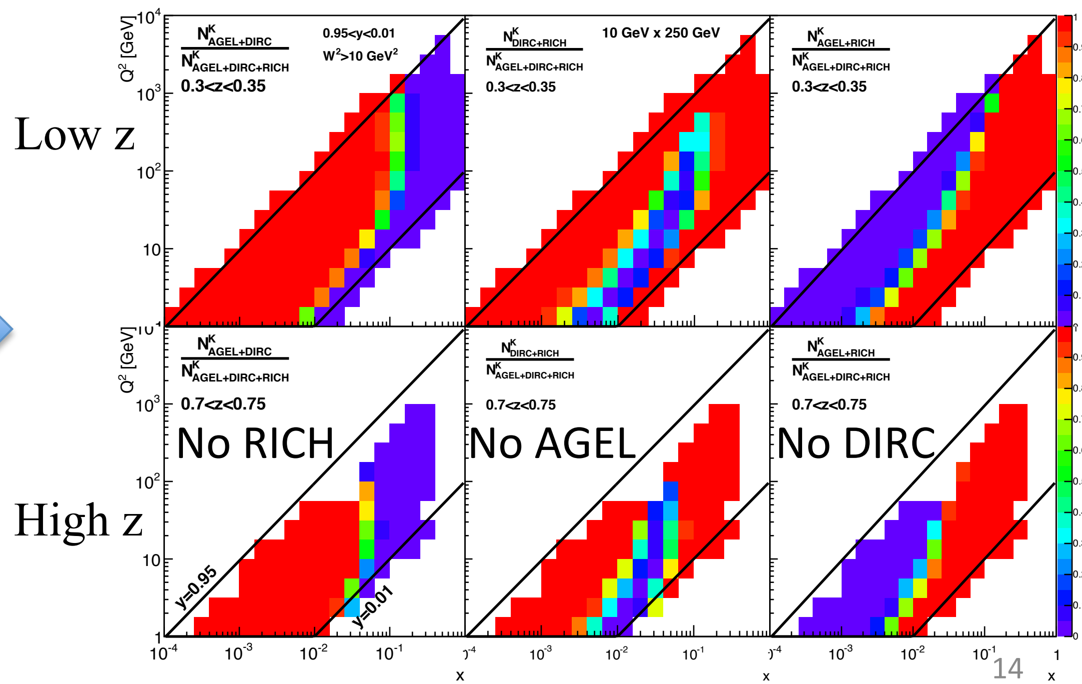
Semi-inclusive DIS and hadron ID





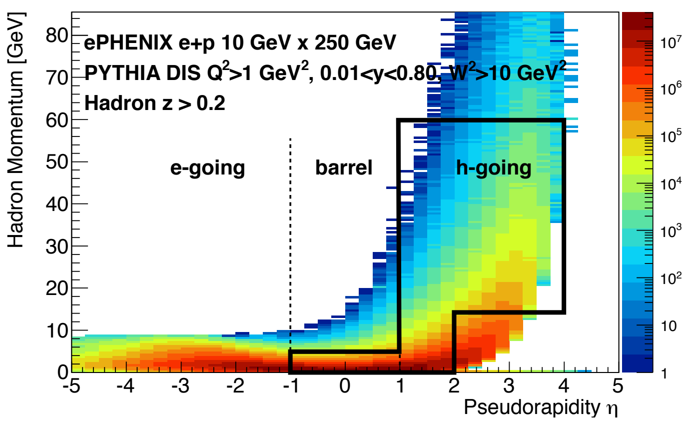
(x,Q²) coverage with K

(x,Q²) loss if not have given detector



All three detectors are important

Hadron ID with gas RICH

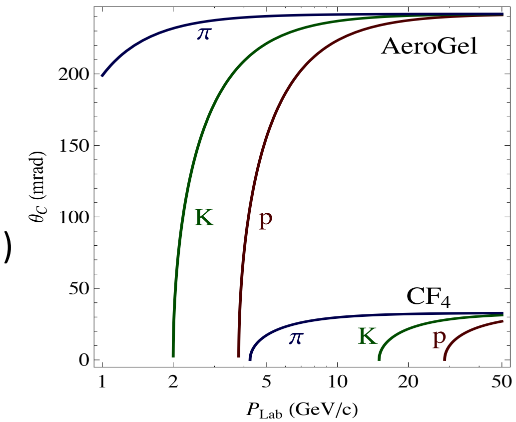


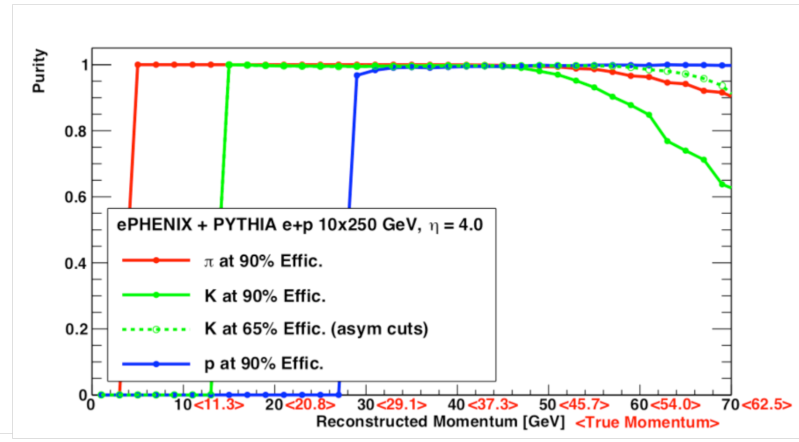
Gas RICH (CF4): 1<η<4

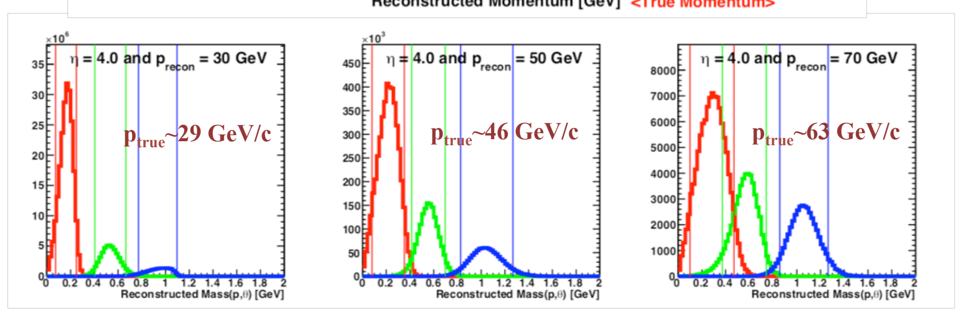
Highest momentum measurements require:

- Good momentum resolution (combination of tracking and HCal)
- Good ring resolution

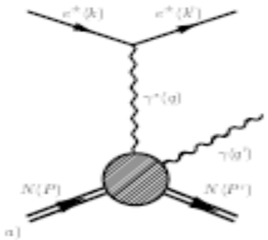
Need to balance efficiency and purity to get best measurement







- PID up to ~60 GeV/c
- Currently limited by ring resolution (2.5% per photon - the current feedback from EIC R&D)
- Much smaller smearing due to magnetic field and off-center-vertex tracks



Exclusive Measurements

DVCS:

Wide coverage for photon measurements

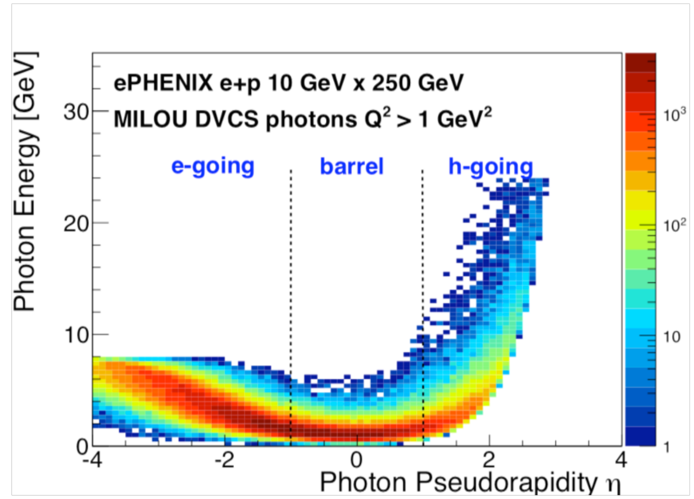
- EMCal and tracking in |η|<4

Separation of e-γ in EMCal

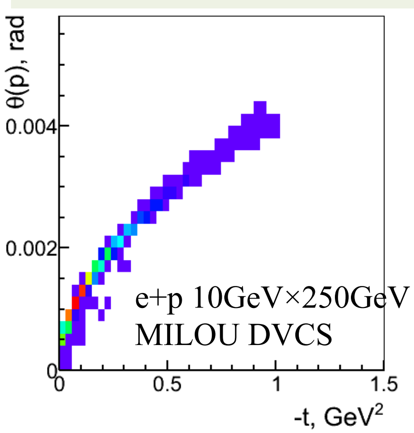
- 0.02×0.02 EMCal granularity is enough

Intact proton detection is highly desirable

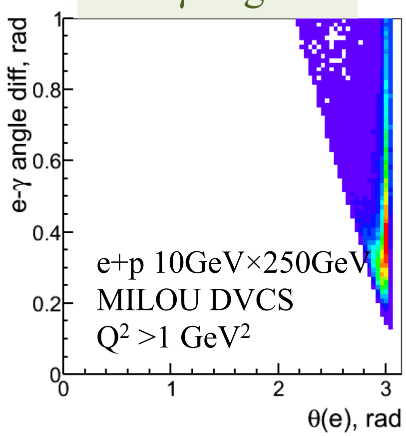
- Roman Pots



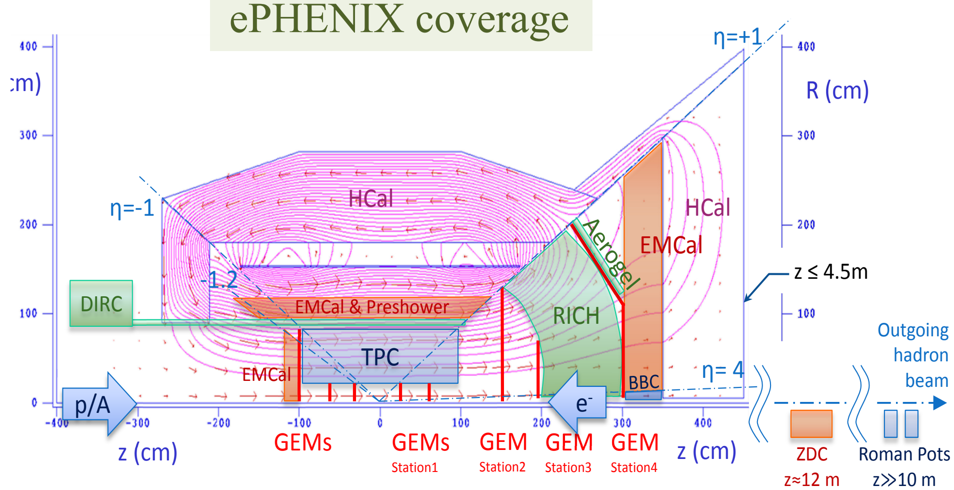
Proton scattering angle



e-γ angle



ePHENIX coverage

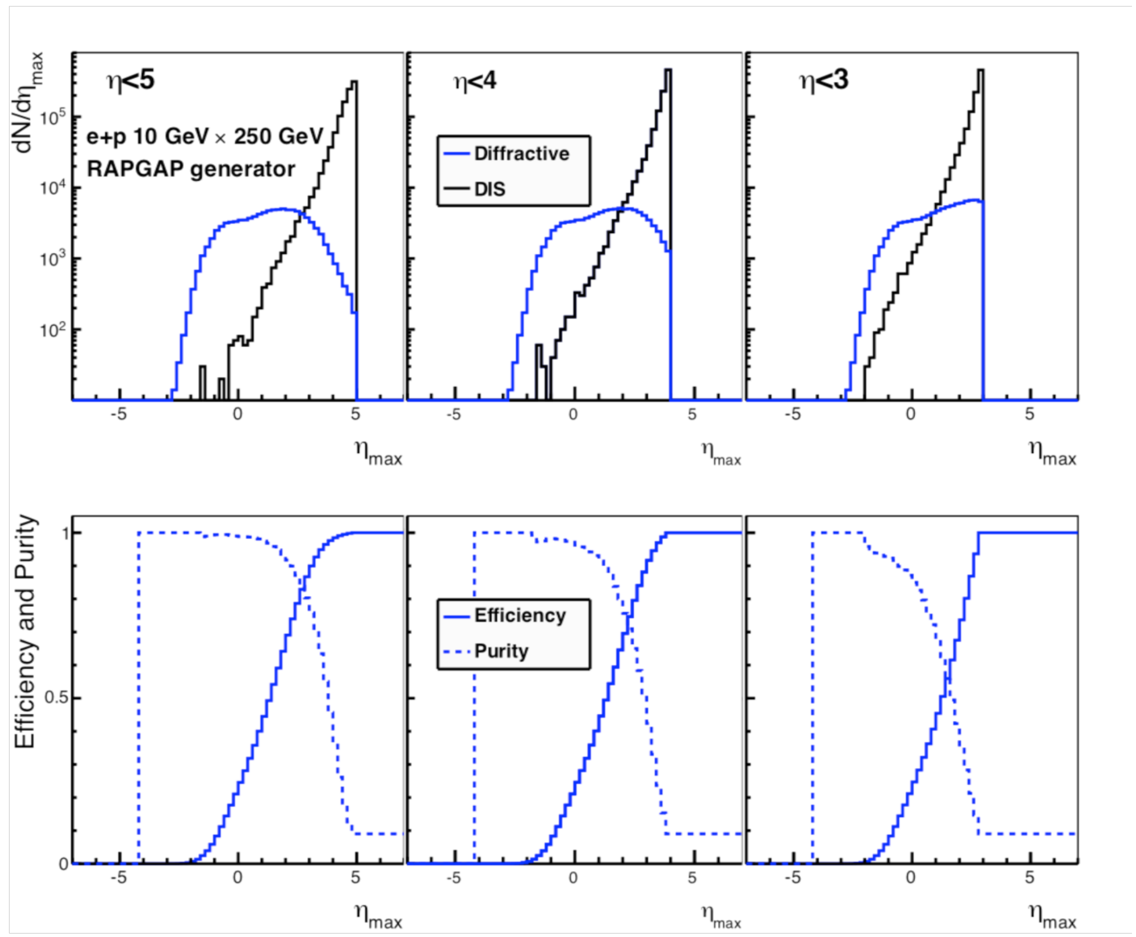


Diffractive Measurements

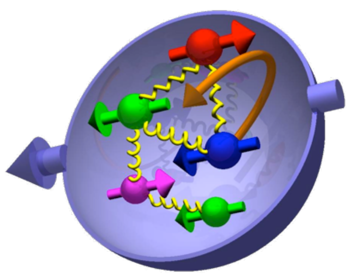
- Measure most forward going particle, to determine rapidity gap

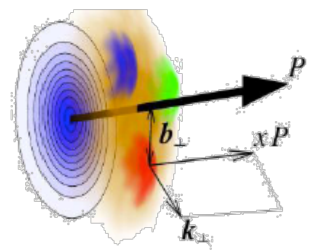
  HCal with -1<η<5 and EMCal with -4<η<4 are excellent in separation of DIS and diffractive

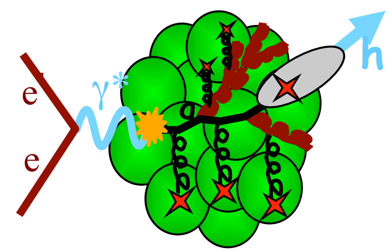
- ZDC to measure nucleus breakup



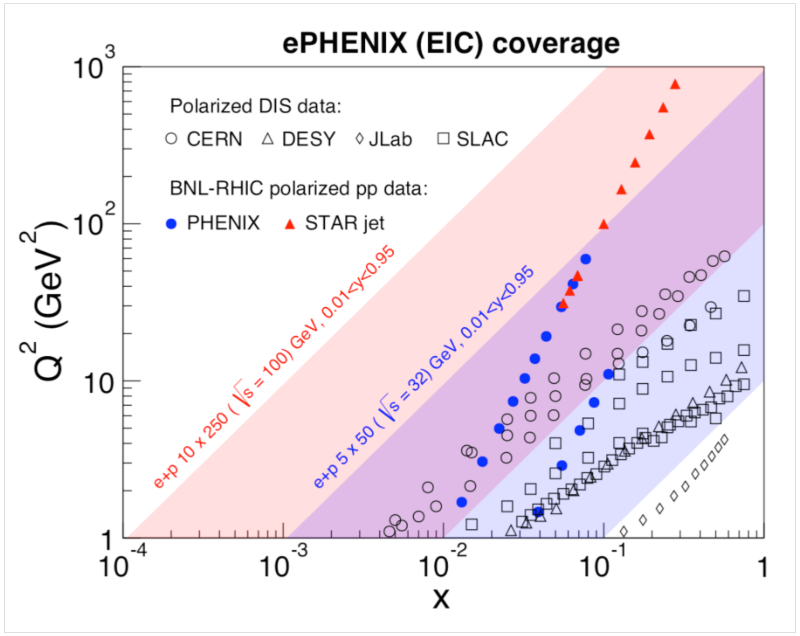
Physics Expectations







Proton structure: long. spin



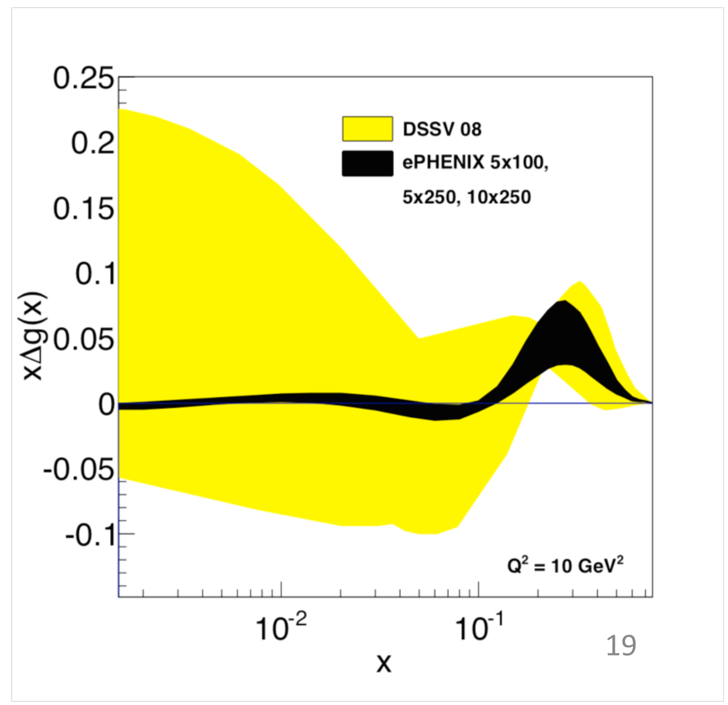
Inclusive and semi-inclusive DIS

Unique capability to reach much lower x and span a wider range in Q^2

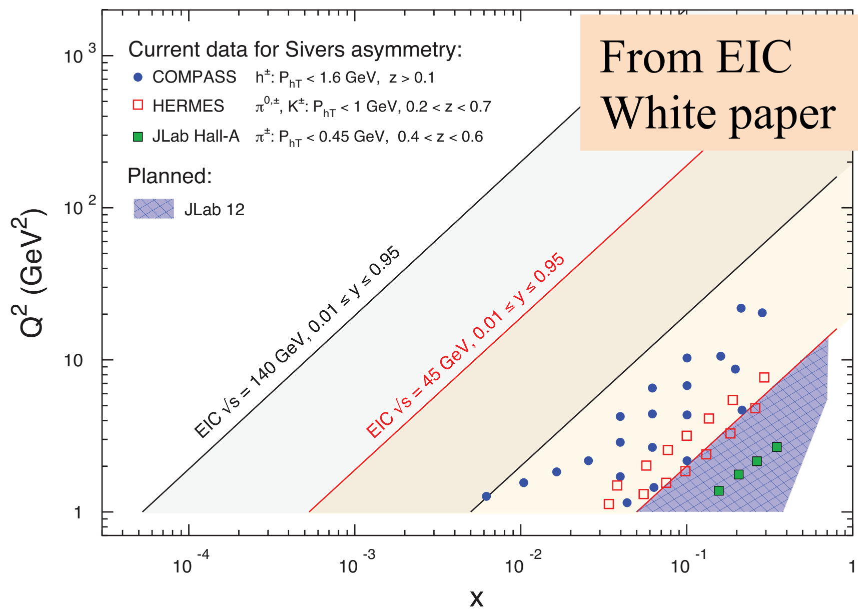
=> Precise evaluation of the long. spin component of the gluons and flavor separated (sea)quarks to the nucleon spin

PHYTHIA generator and ePHENIX acceptance/efficiencies

10 fb^{-1} in each energy configuration: 5×100, 5×250, 10×250



Motion of confined gluons and quarks



Semi-inclusive DIS

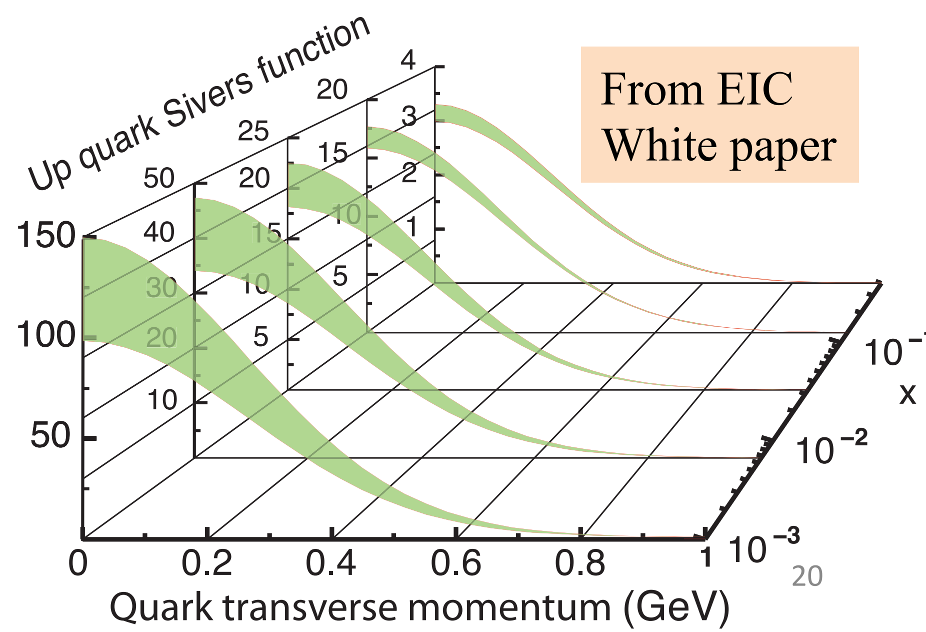
Transverse Momentum Distributions (Sivers)

Greatly expand x&Q^2 coverage

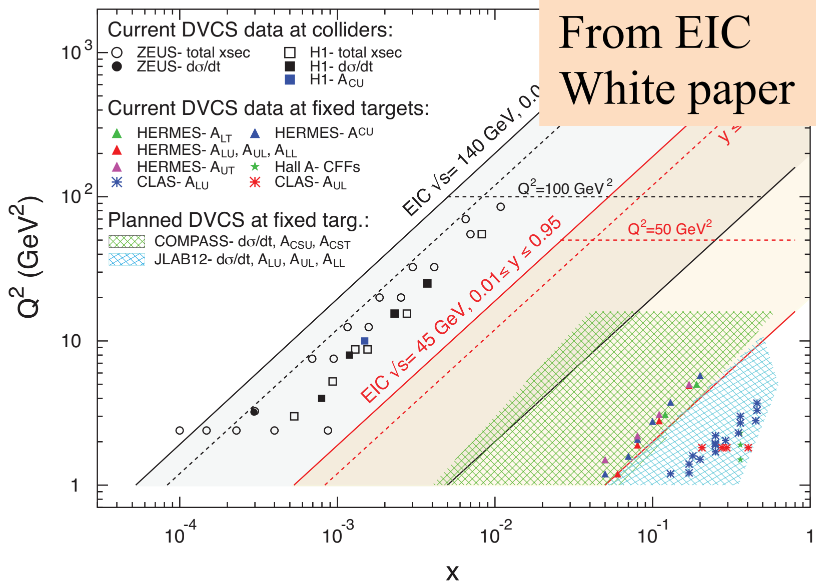
High luminosity => fully differential analysis over x, Q^2, z and P_{hT}

For the first time, determination of Sivers distributions over wide range in x will be possible

We're working on evaluation of expected Sivers constraint with ePHENIX data



Proton Tomography



From EIC White paper

Exclusive DIS

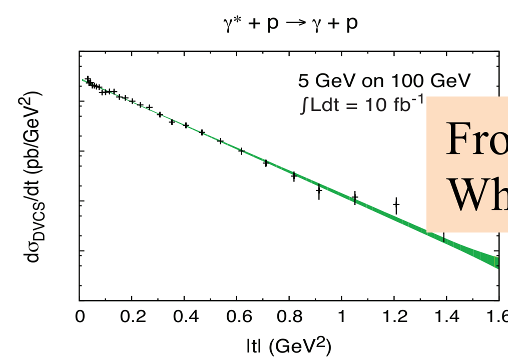
Generalized Parton Distributions

Connected to parton orbital angular momentum

Existing data are either at low Q^2 or have sizable stat. uncertainties

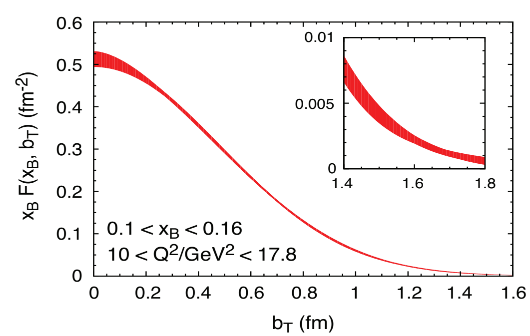
Provide data in wide x&Q^2

Precise imaging requires higher e-beam energy and luminosity

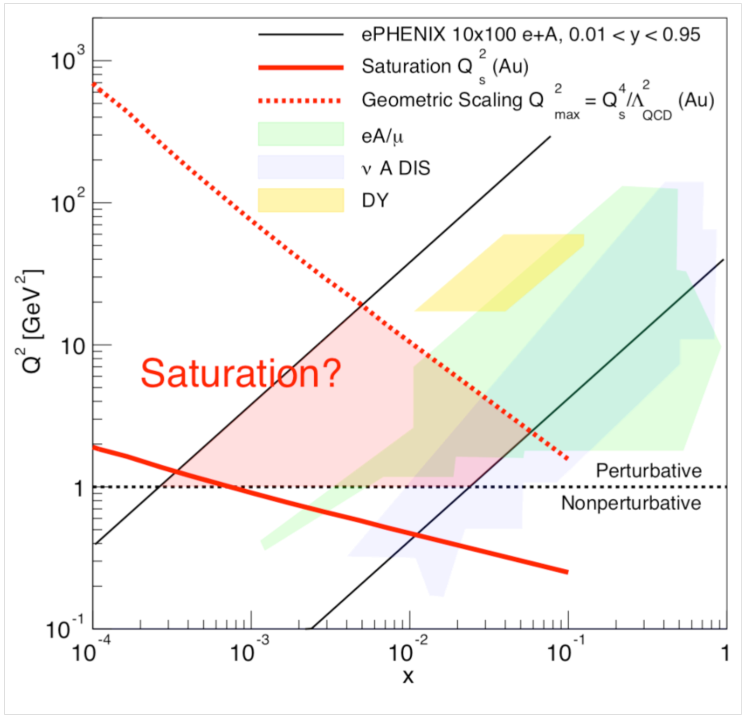


From EIC White paper

ePHENIX with its EMCal and tracking coverage is expected to do similar job (e.g with DVCS)



Gluon Saturation



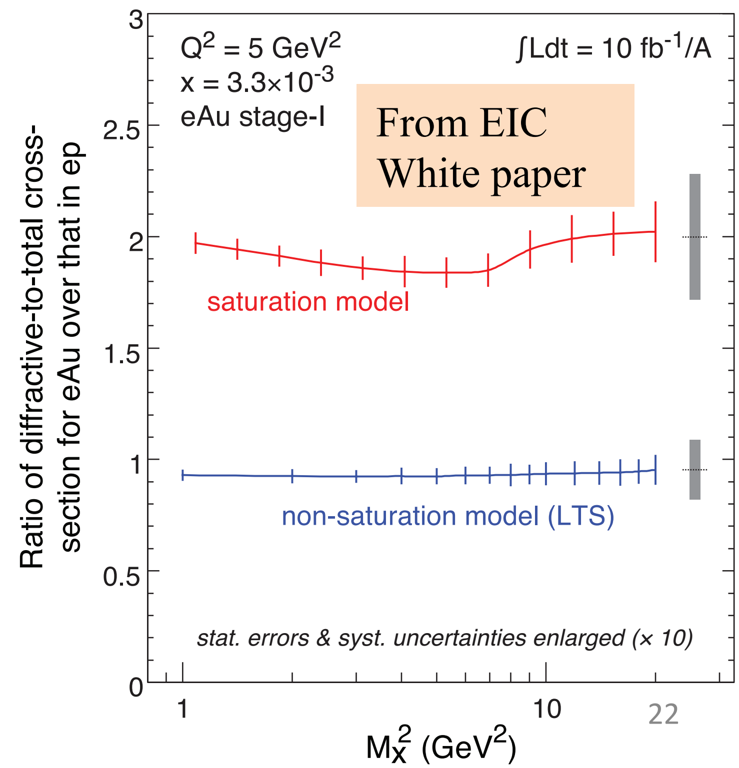
$$Q_s^2(x) \propto \left(\frac{A}{x}\right)^{1/3}$$

Saturation effects are greatly enhanced in eA collisions:

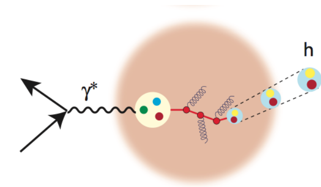
Collider energy -> low x

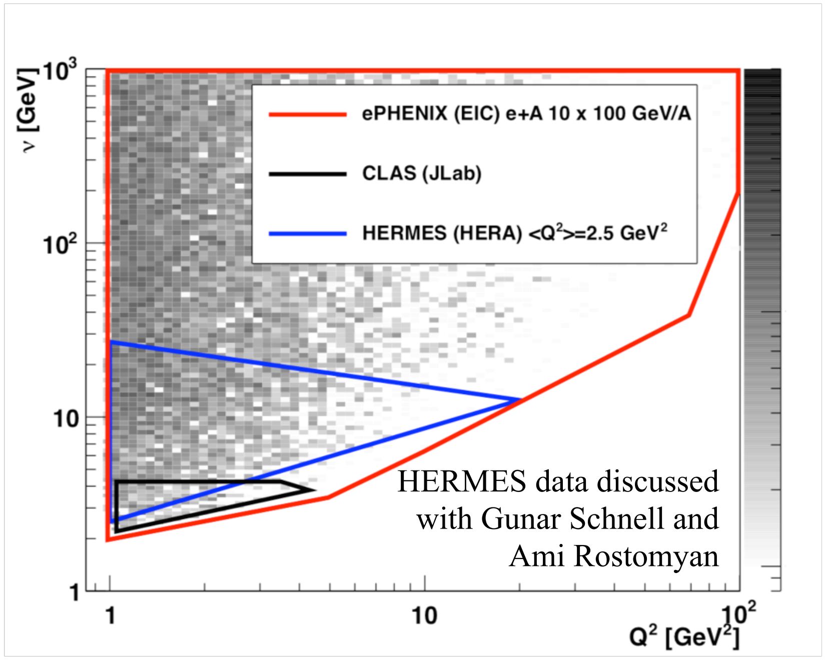
Heavy Ions -> high A

ePHENIX with its HCal and EMCal coverage is expected to do similar job (with diffractive measurements)



Hadronization





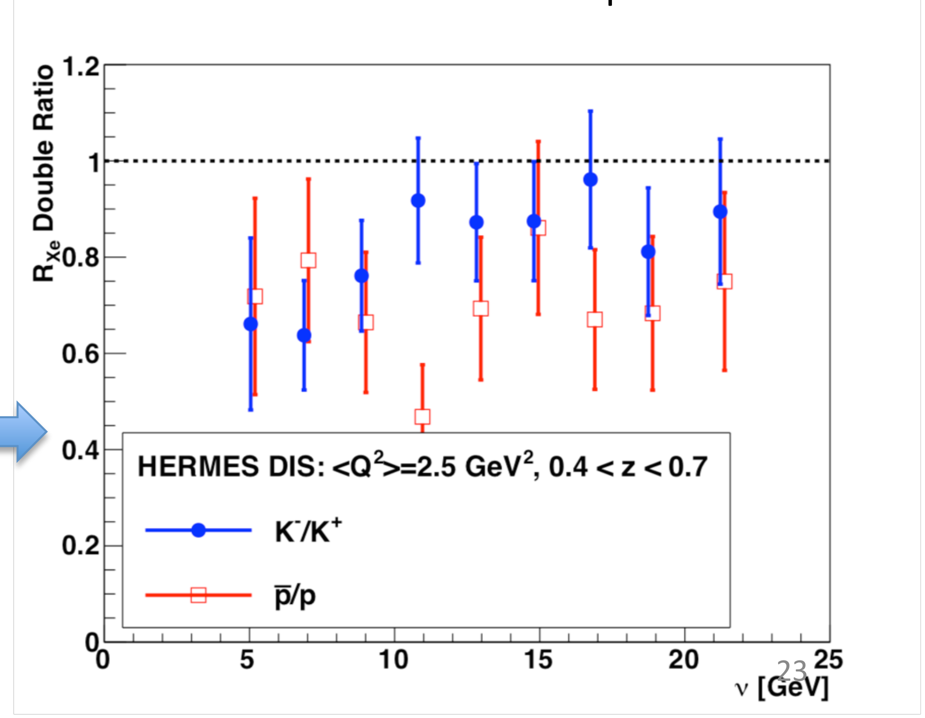
Semi-inclusive eA

Probe color neutralization and hadronization

Previous experiments are limited by low ν, Q^2

eRHIC:

- Much larger range of ν, Q^2
- Wide range of nuclear size
- Excellent ePHENIX hadron PID up to 60 GeV



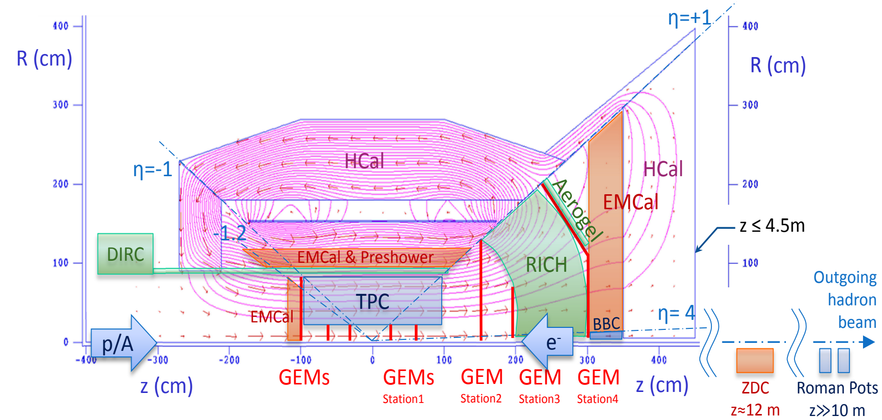
ePHENIX with its excellent hadron PID at eRHIC with its high luminosity and wide kinematic reach, is expected to provide much smaller uncertainties in wider range of ν, Q^2 and nucleus size

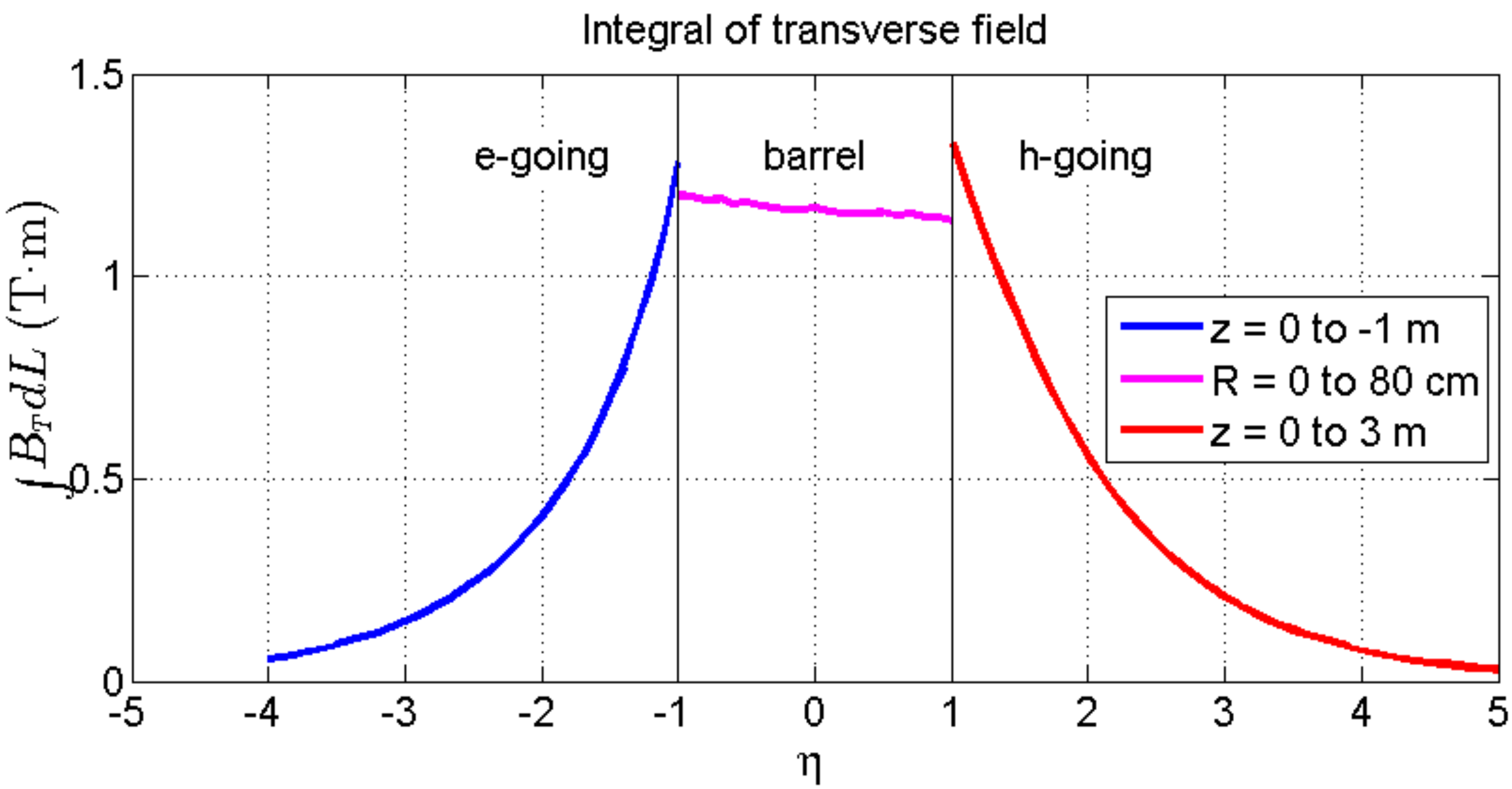
Evaluation is ongoing

Summary

Backup

B_TdL


R (cm)
η=+1
R (cm)
η=-1
HCal
HCal
EMCal
Aerogel
z ≤ 4.5m
DIRC
-1.2
EMCal & Preshower
RICH
TPC
EMCal
η= 4
BBC
Outgoing hadron beam
p/A
e⁻
z (cm)
GEMs
GEMs Station1
GEM Station2
GEM Station3
GEM Station4
z (cm)
ZDC z≈12 m
Roman Pots z≫10 m


Integral of transverse field
e-going
barrel
h-going
z = 0 to -1 m
R = 0 to 80 cm
z = 0 to 3 m
∫B_T dL (T·m)
η

TPC

LEGS TPC

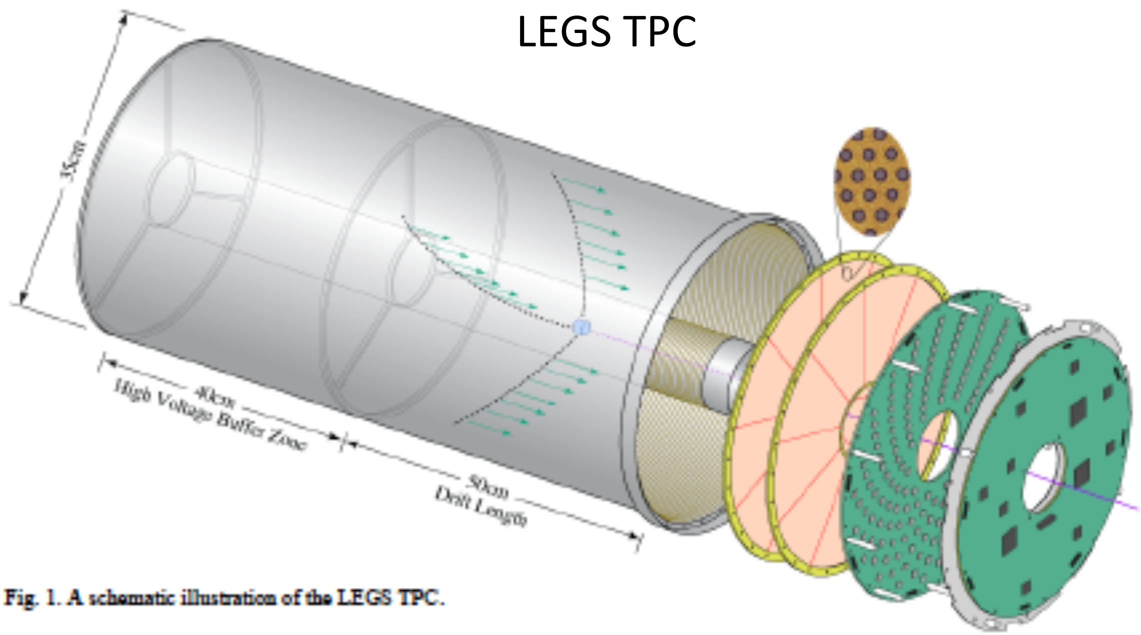
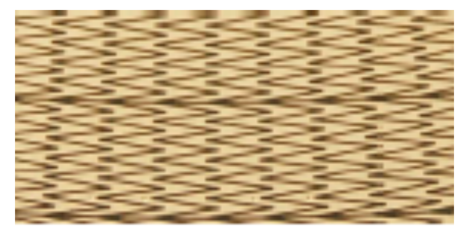


Fig. 1. A schematic illustration of the LEGS TPC.

Chevron-type readout pattern with a pad size 2mm × 5mm

Achieved pos. res. 200 μm



ePHENIX TPC:

R=15-80cm, |z|<95cm

Gas mixture with fast drift time: 80% Ar, 10% CF_4, 10% CO_2

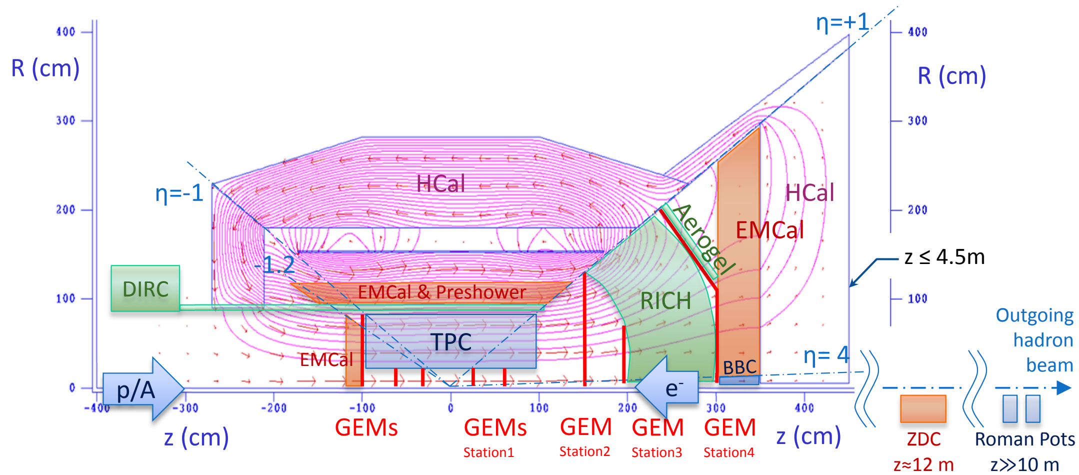
For 650 V/m -> 10cm/μs -> Drift time 10 μs

2×10mm pads –> 180k pads (both ends readout)

Pos. resolution 300 μm (twice longer drift distance tha LEGS)
and 40 readout rows => $\sigma_p/p \sim 0.4\%\times p$

Tracking with GEM

Improved pos. res.
with mini-drift GEM



e-going direction

Station 1-2: z=30, 55cm r=2-15cm
Station 3: z=98 cm
-3<η<-2: 50μm with 1mm pad
-2<η<-1: 100μm with 2mm pad
Δr=1cm for St1-2 and Δr=10cm for St3

h-going direction

Station 1: z=17 and 60cm with r=2-15cm
Station 2-4: z=150, 200, 300 cm, 1<η<4
2.5<η<4: 50μm with 1mm pad
1<η<2.5: 100μm with 2mm pad
Δr=1-10cm

Collision vertex is necessary in e-going direction:

BBC: η=4-5, z=3m, σ_t=30ps (with MRPC or MCP) -> σ_z=5mm -> const term in σ_p/p~2%

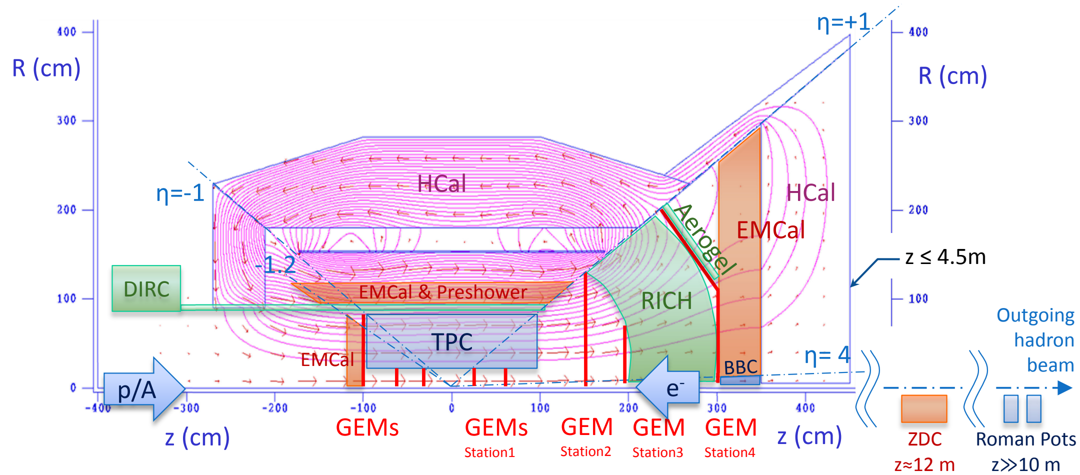
Total channel count: 217k

Large area GEMs are being developed in CERN for CMS (needed for our St 2-4)

Calorimetry

EMCal coverage -4<η<4
HCal coverage -1<η<5

Readout: SiPM



e-going direction

Crystall EMCal:

- 2cm×2cm
- 5k towers
- $\sigma_E/E \sim 1.5\%/\sqrt{E}$
- $\sigma_x \sim 3mm/\sqrt{E}$

Barrel (sPHENIX)

Tungsten-fiber EMCal:

- 2cm×2cm
- 25k towers
- $\sigma_E/E \sim 12\%/\sqrt{E}$

Steel-Sc HCal:

- 10cm×10cm
- 3k towers
- $\sigma_E/E \sim 100\%/\sqrt{E}$

h-going direction

Pb-fiber EMCal:

- 3cm×3cm
- 26k towers
- $\sigma_E/E \sim 12\%/\sqrt{E}$

Steel-Sc HCal:

- 10cm×10cm
- 3k towers
- $\sigma_E/E \sim 100\%/\sqrt{E}$

Hadron PID

DIRC

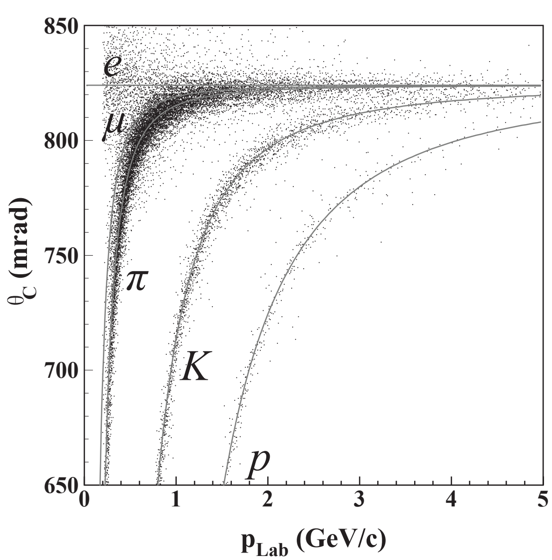
$-1<\eta<1$
Mirror focusing ?
Threshold for $\pi/K/p$:
0.2/0.7/1.5 GeV

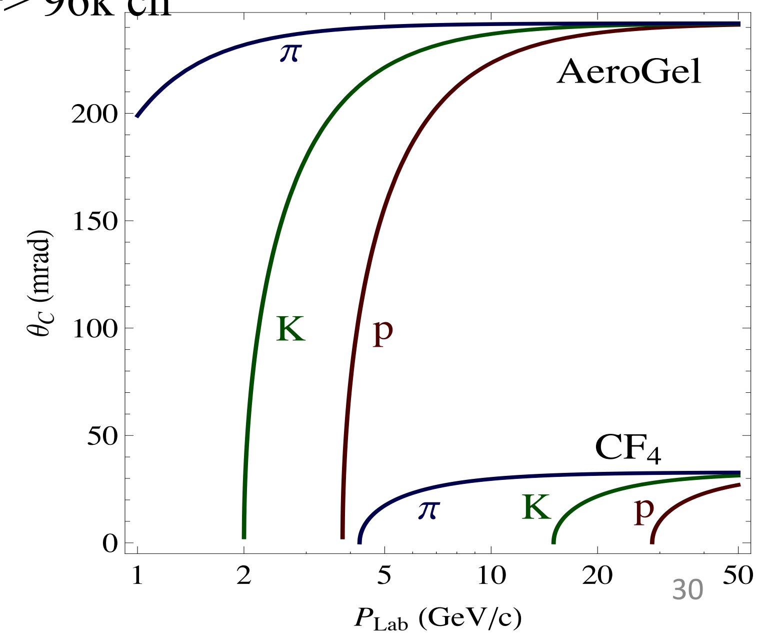
Gas RICH (CF4)

$1<\eta<4$
Mirror focusing
Threshold for $\pi/K/p$:
4/15/29 GeV
6 azimuthal segments
Photodetection: GEM with CsI
Area $6\times0.3m^2$ –> 96k ch
In gas volume!

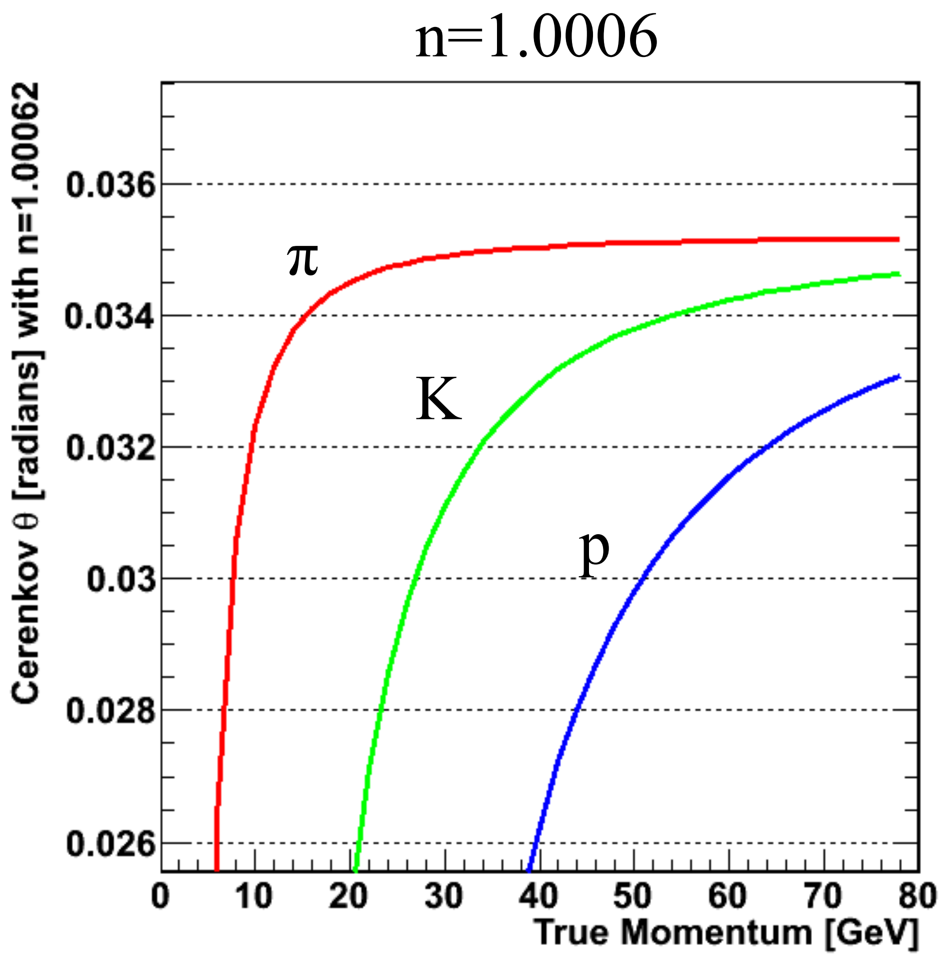
Aerogel

$1<\eta<2$
Proximity focused
Threshold for $\pi/K/p$:
0.6/2/4 GeV





Cerenkov Angle in CF4



Hadron PID: gas RICH

Goals and assumptions/restrictions

1m gas volume along the track => F=1m => R=2m

Z>1.5m (optimal sagitta plane)

Z<3.0m (EMCal)

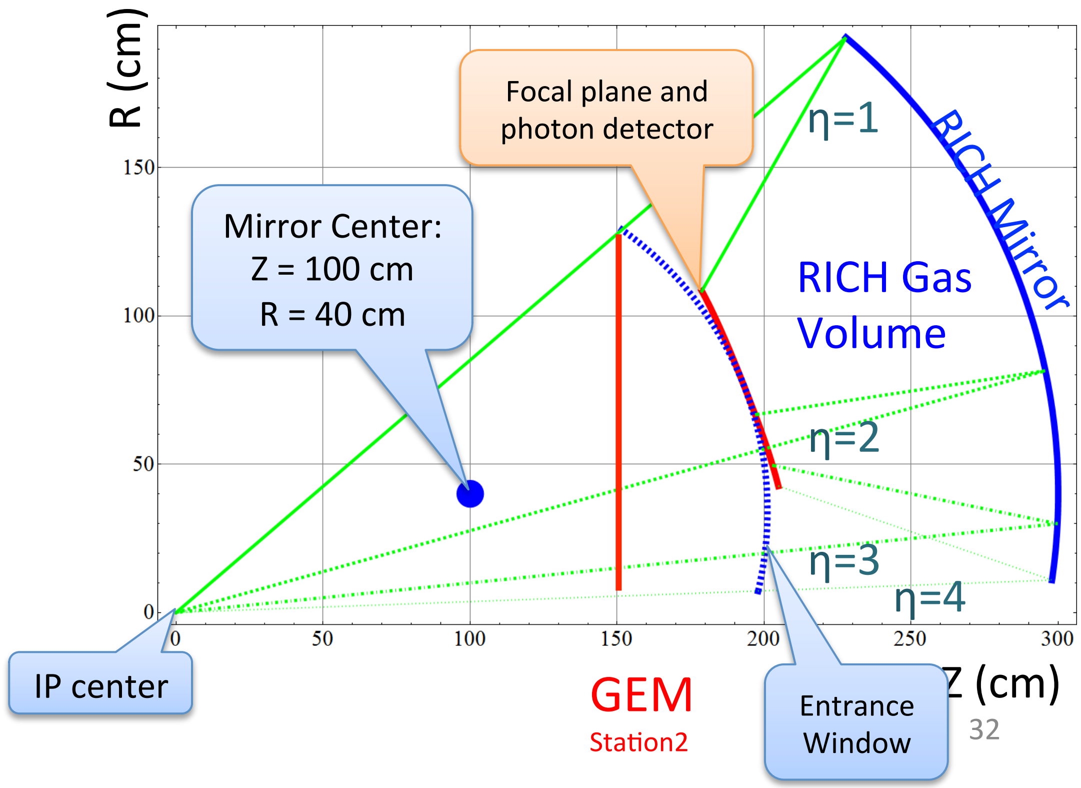
Photon detector inside tracking volume –> GEM as thin –> flat

Low number of edges between mirrors

Small area for photon readout

Moving mirror center to beam line:

- Focal plane not flat
- Steeper impact angle on the photon detector
- Photon detector closer to beam line
- RICH volume moves to z<1.5m



Hadron PID: gas RICH

CF4 (n=1.00062)

Ring resolution

Ring radius resolution: $2.5\%/\sqrt{N_\gamma}$

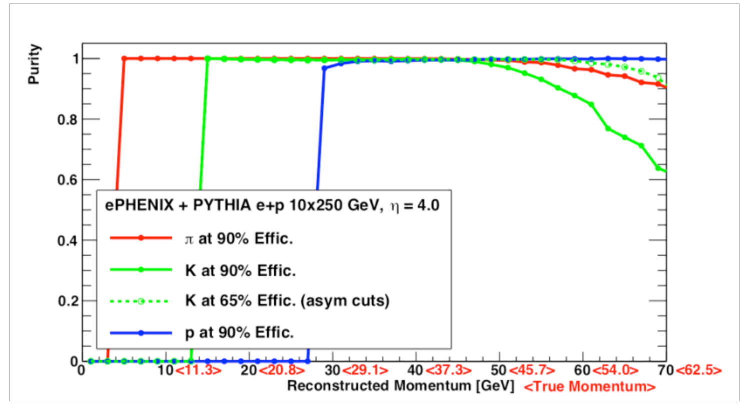
- From current EIC R&D studies
- LHCb and COMPASS claimed 1% per photon

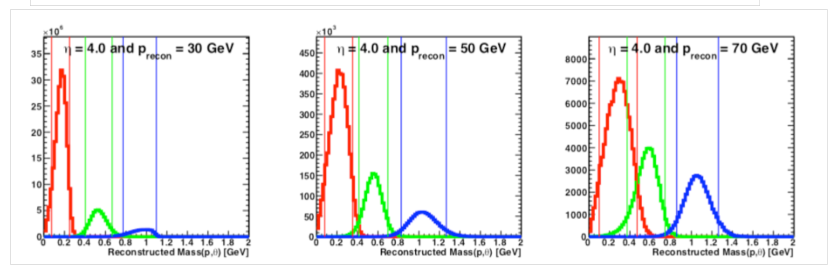
Residual magnetic field (~0.5 T) bends tracks radiating photons => ring smearing

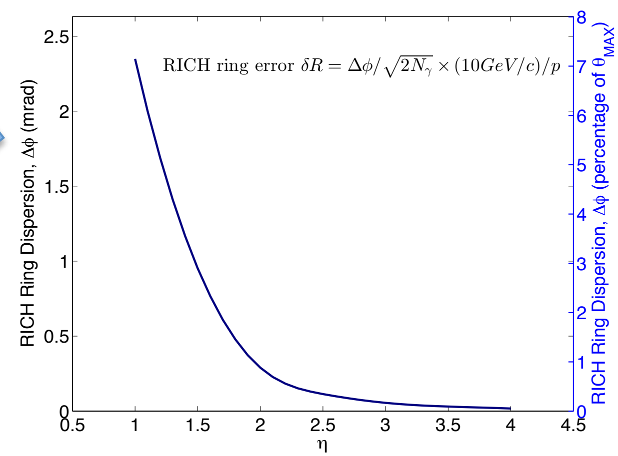
- Since field is near parallel to tracks the effect is minimal

Off-center vertex tracks have shifted focal plane => ring smearing

- For $\eta=1$ and z=40cm => ring dispersion $5\%/\sqrt{N_\gamma}\times(10\ \mathrm{GeV/c})\ /\ p$
- For larger η effect is smaller





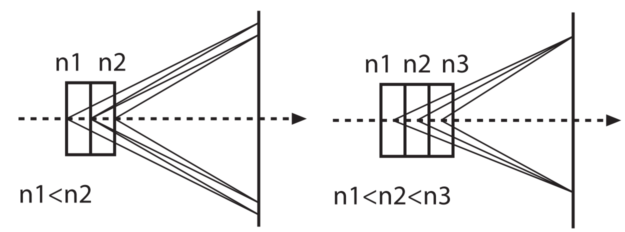


Ring resolution limits PID at higher p

Hadron PID: Aerogel

Allows to identify K for 3<p<10 GeV

Focusing



Challenges:

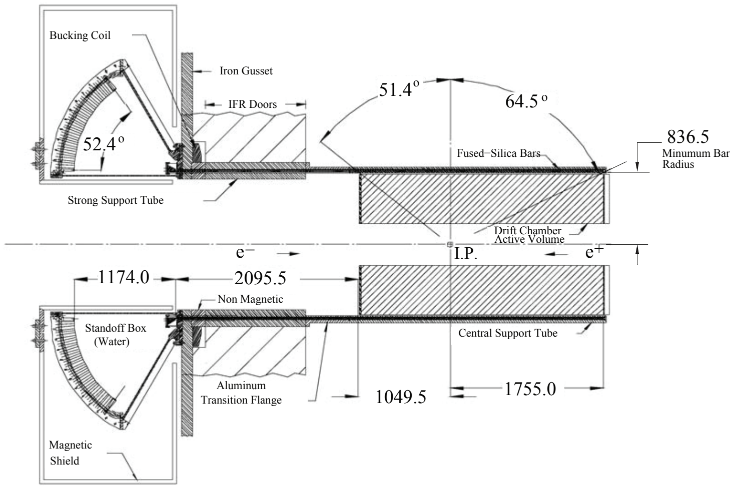
- Fringe field
- Low light output
- Visible wavelength range
- Limited space for light focusing

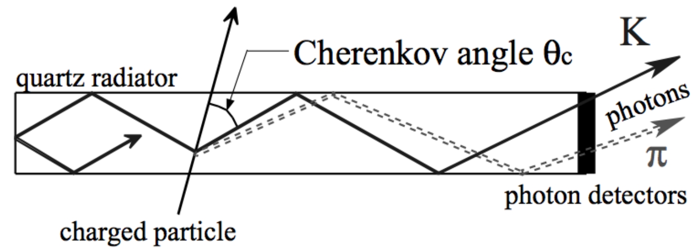
Photon detection:

Microchannel Plate Detector

- Multi-alkali photocathode
- Also ToF with σ=20-30ps
- Being developed by LAPPD Collaboration

Hadron PID: DIRC





BaBar DIRC

Quartz radiator bars, Cerenkov light internally reflected

No focusing => Large water filled expansion volume

PMT for readout

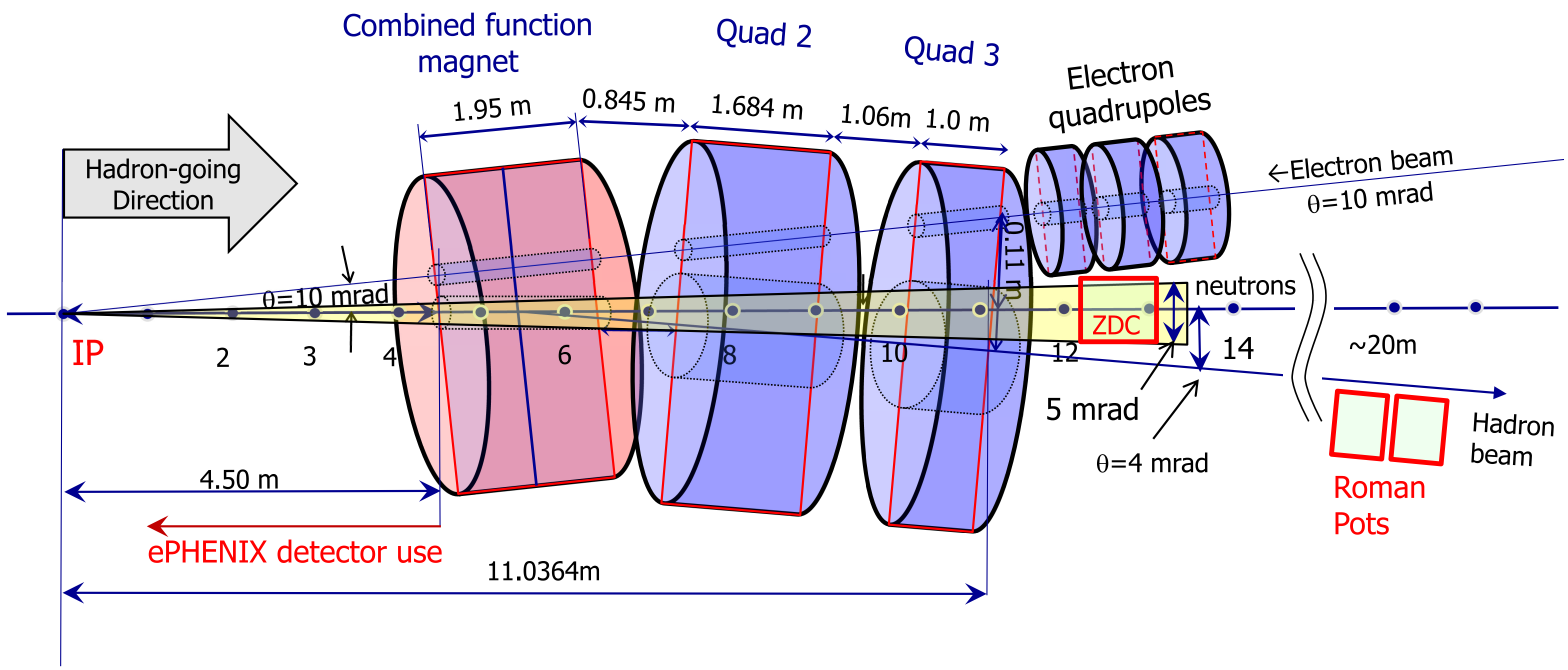
ePHENIX DIRC

Mirror Focusing to avoid large expansion region

Pixelated multi-anode PMT for readout

Ring resolution limits PID at higher p

Beamline Detectors



ZDC

12 m downstream

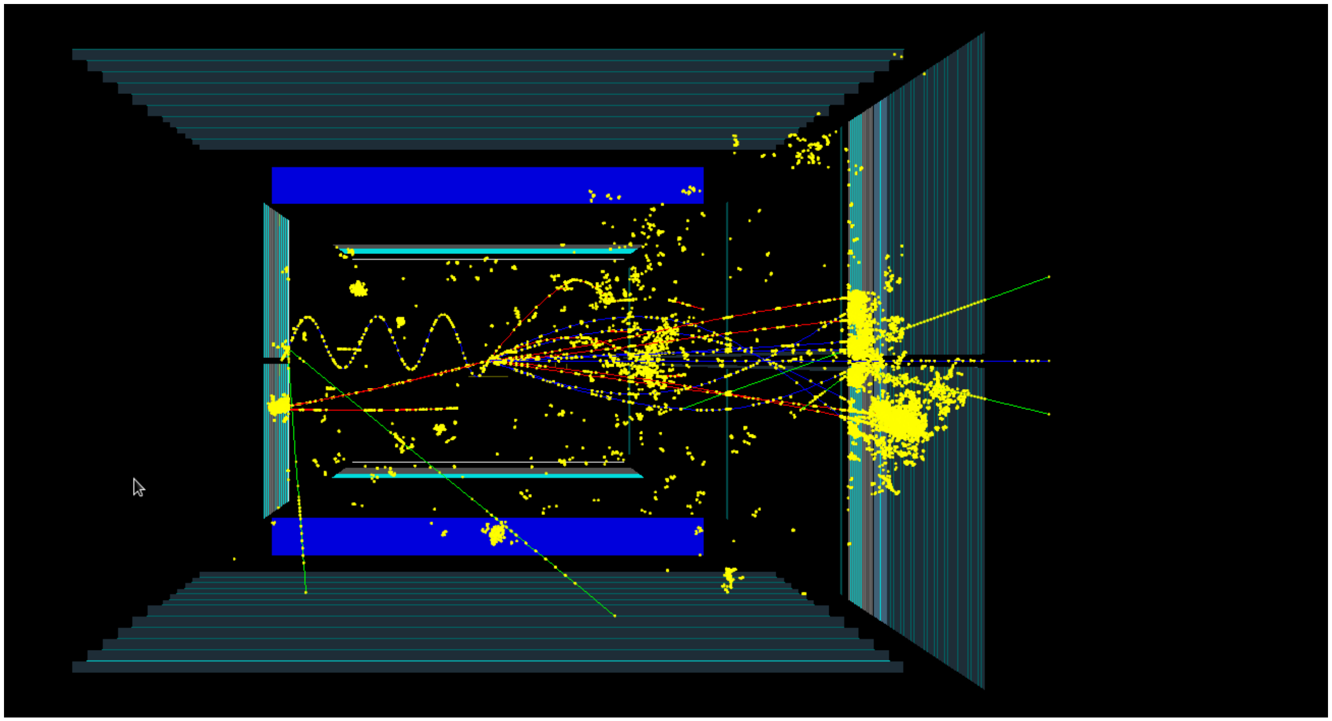
5 mrad cone opening of the IP is available from ePHENIX and IP design

Roman Pots

>20 m downstream

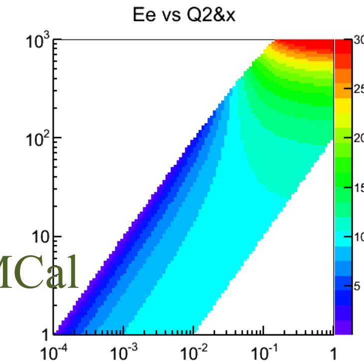
Similar to STAR design

GEANT simulation



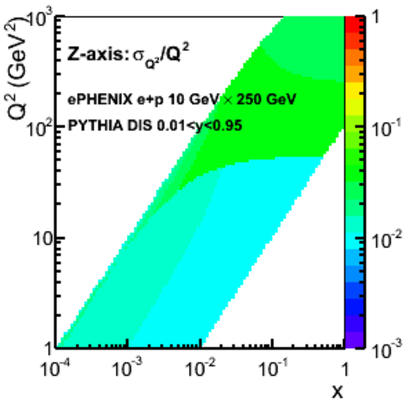
GEANT4 description of ePHENIX exists
Simulation and analysis software common with sPHENIX and PHJENIX

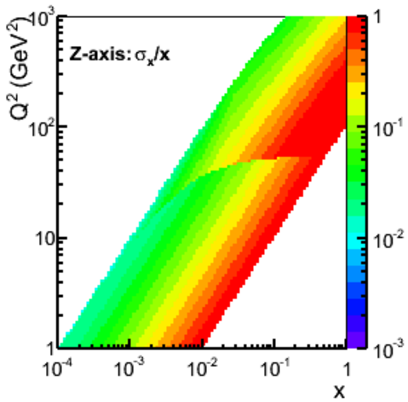
DIS kinematics: angle from EMCal

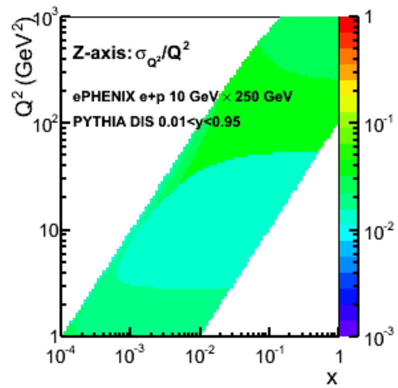


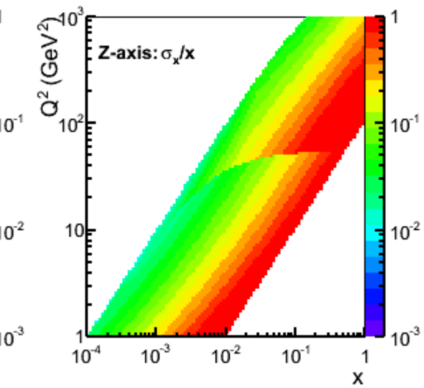
With perfect angle measurements

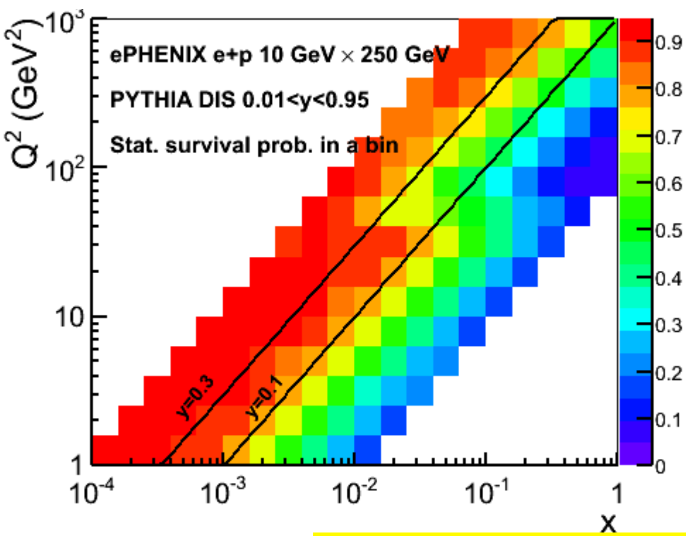
With angle smearing due to EMCal pos. resolution

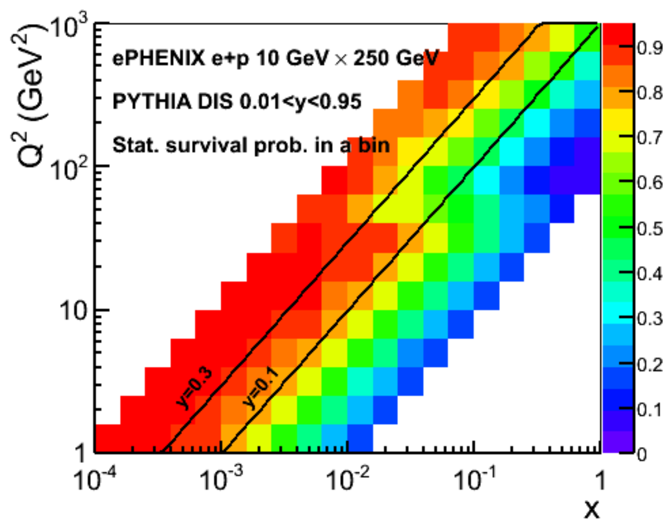








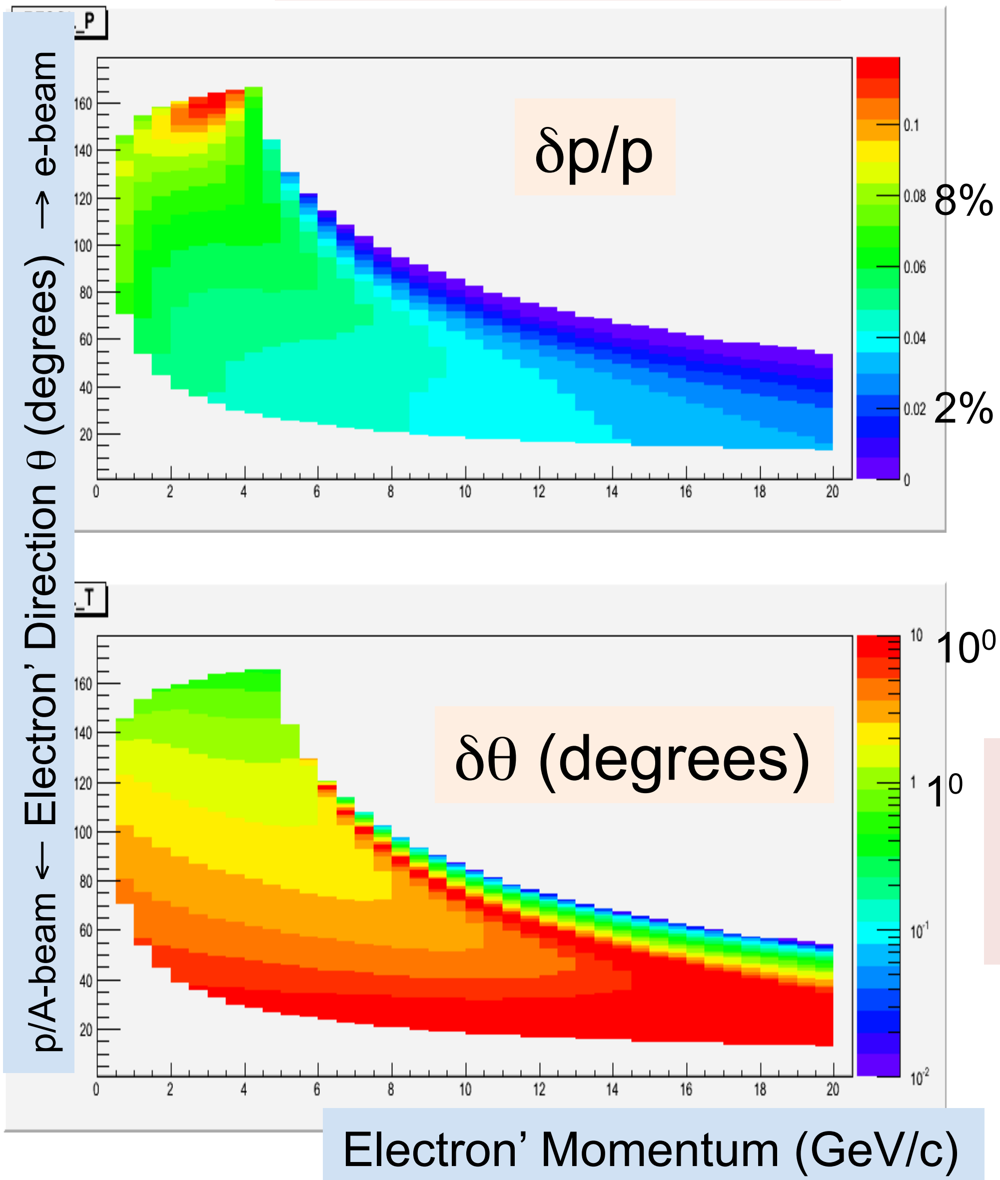




Only minor effect from angle measurements with EMCal

Tom H: Momentum and angle resolution

5 GeV (e) × 100 GeV (p)



Inclusive measurements:

$$\sigma_{red} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

$$(x,Q^2) \rightarrow (p,\theta)_{e'}$$

Resolution → Systematics → Unfolding

Assume: σ_{syst}~1/5 of systematics

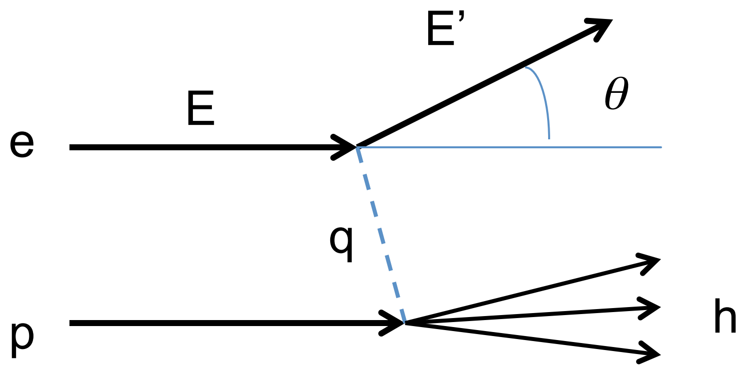
0.1×0.1 binning in $\log_{10}(x) \times \log_{10}(Q^2)$

Require: 1% uncertainty in each bin

"Reasonable" resolutions may be enough:

$\delta p/p \sim$ 2-8%

$\delta\theta \sim$ 1 degree



Electron vs Jacquet-Blondel

Electron

$$Q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E}\cos^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

JB

$$Q^2_{JB} = \frac{p^2_{T,h}}{1 - y_{JB}} \qquad p^2_{T,h} = \left(\sum_h p_{x,h}\right)^2 + \left(\sum_h p_{y,h}\right)^2$$

$$y_{JB} = \frac{(E - p_z)_h}{2E_e} \qquad (E - p_z)_h = \sum_h (E_h - p_{z,h})$$

$$x_{JB} = \frac{Q^2_{JB}}{sy_{JB}}$$

$y \to 0$: $\sigma_y/y \sim 1/y$

$y \to 0$: $\sigma_y/y \sim \text{const}$

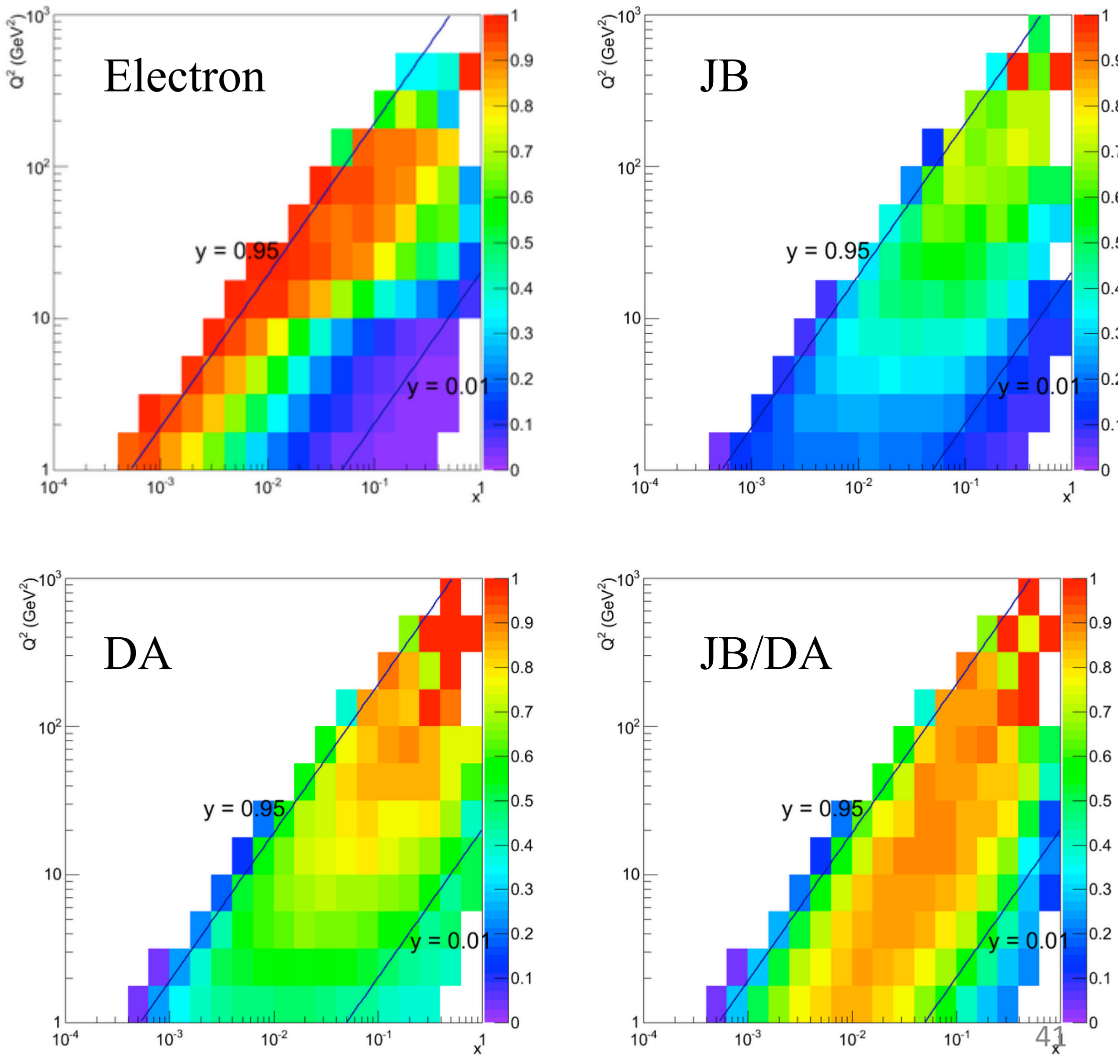
JB

EIC group studies:
https://wiki.bnl.gov/eic/index.php/Q2-x_bin_migration

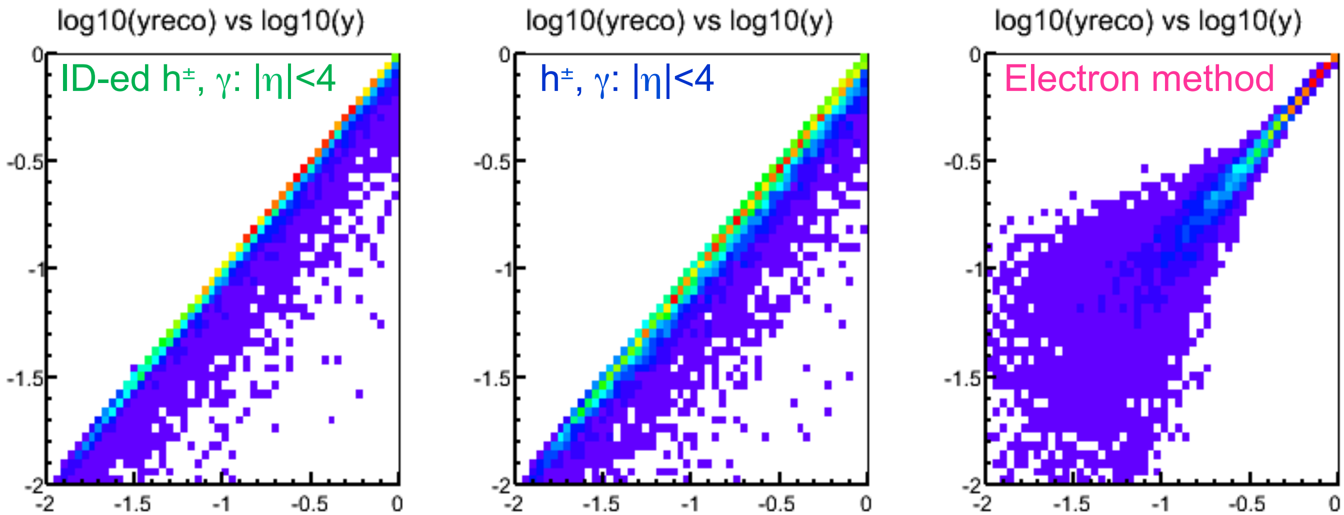
JB and DA methods give better resolution at lower y and higher Q^2

Our studies:

- Enough to measure hadrons in $|\eta|<4$
- Hadron PID is important
  - Particularly for lower Q^2
- For $y<0.2$ – enough to measure in $-1<\eta<4$
  - The acceptance we'll equip with hadron ID



JB: 5x100 Q2>10



- Enough to measure hadrons in |η|<4
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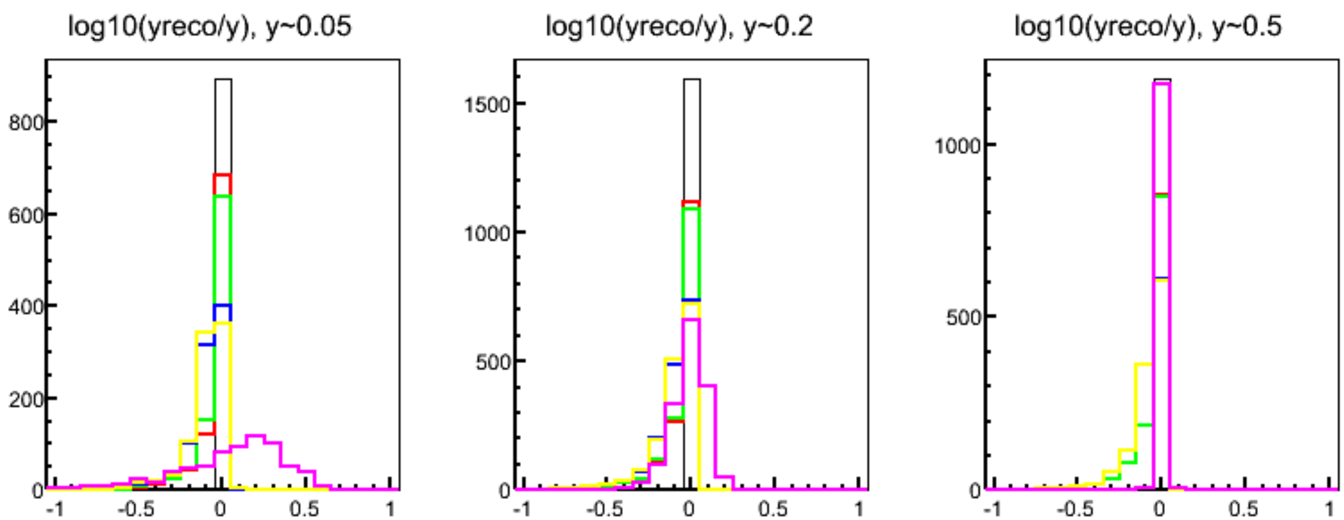
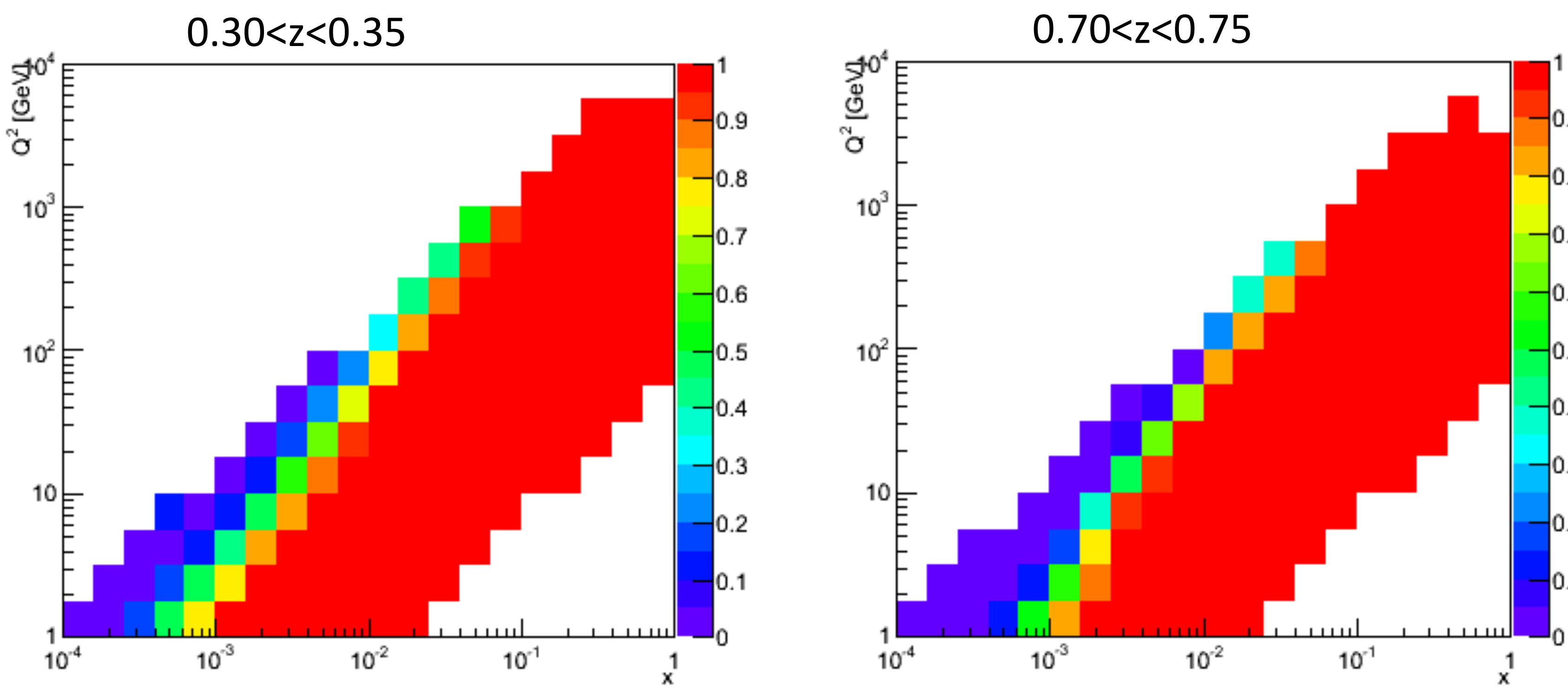


All
ID-ed h±, γ
ID-ed h±, γ: |η|<4
h±, γ: |η|<4
h±, γ: |η|<4, p-smeared
Electron method

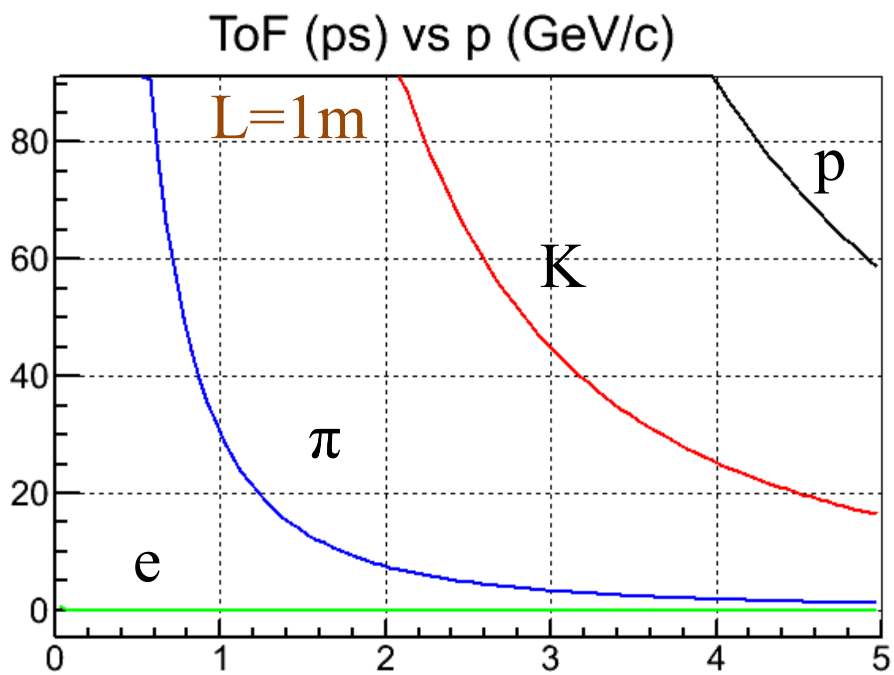
Green ~ Red
Blue ~ Yellow

(x,Q2) loss due to no ePID in e-going direction

e+p 10 GeV × 250 GeV
PYTHIA DIS 0.01<y<0.95 W^2>10 GeV^2



ToF for PID?



With 10 ps resolution including t_0:

e/π separation at <1 GeV/c

K/π separation at <4 GeV/c

Need t_0 (σ<10ps) and vertex (σ~1mm)

Cost and schedule

Table 4.1: Estimated equipment costs for the ePHENIX detector (in $M).

		Cost	Overhead	Contingency	Total
Calorimeters	Endcap Crystal	3.40	0.47	1.93	5.80
	Forward EMCAL	1.41	0.27	0.84	2.53
	Forward HCAL	3.90	0.68	2.29	6.87
Tracking	TPC	0.75	0.19	0.47	1.41
	GEM Trackers	0.71	0.18	0.44	1.33
Beamline instrumentation	Roman pots	0.23	0.04	0.14	0.41
	Beam-Beam counter	0.20	0.05	0.13	0.38
Particle ID	DIRC	12.50	1.75	7.13	21.38
	RICH	2.00	0.50	1.25	3.75
	Aerogel	1.55	0.22	0.88	2.65
Electronics/sensors	Endcap Crystal	0.89	0.22	0.56	1.67
	Forward EMCAL	3.09	0.43	1.76	5.28
	Forward HCAL	0.38	0.05	0.22	0.65
	TPC	2.80	0.81	1.81	5.42
	GEM Trackers	0.71	0.18	0.44	1.33
	DIRC	0.77	0.19	0.48	1.44
	RICH	3.10	0.78	1.94	5.81
	Aerogel	1.55	0.39	0.97	2.91
	Roman Pots	0.11	0.03	0.07	0.21
	Beam-Beam	0.10	0.02	0.06	0.19
	Data Collection	0.60	0.15	0.38	1.13
	Trigger	0.60	0.15	0.38	1.13
Integration/Mechanical		3.00	0.93	1.96	5.90
Total		44.35	8.68	26.51	79.54

Table 4.2: Total estimated labor for ePHENIX detector construction.

	FY21	FY22	FY23	FY24	Total
Physicist FTE	10	9	10	13	42
Physicist cost	3.02	2.78	3.45	4.60	13.85
Engineer FTE	10	10	7	5	31
Engineer cost	2.59	2.66	2.02	1.49	8.76
Technician FTE	1	1	11	19	31
Technician cost	0.21	0.21	2.29	4.16	6.87
Total FTE	20	19	28	37	104
Total cost	5.81	5.65	7.77	10.25	29.49

Table 4.3: Schedule of Critical Decisions and reviews necessary for construction FY2021–FY2024.

CD0	4Q2016
CD1 review	4Q2017
TDR preparation	4Q2017 - 3Q2019
CD2/3 review	4Q2019
FY2021 budget briefing	1Q2020
Construction start	4Q2020 (FY2021)
CD4	3Q2024 (FY2024)
Commissioning run	1Q2025